University of Chinese Academy of Sciences

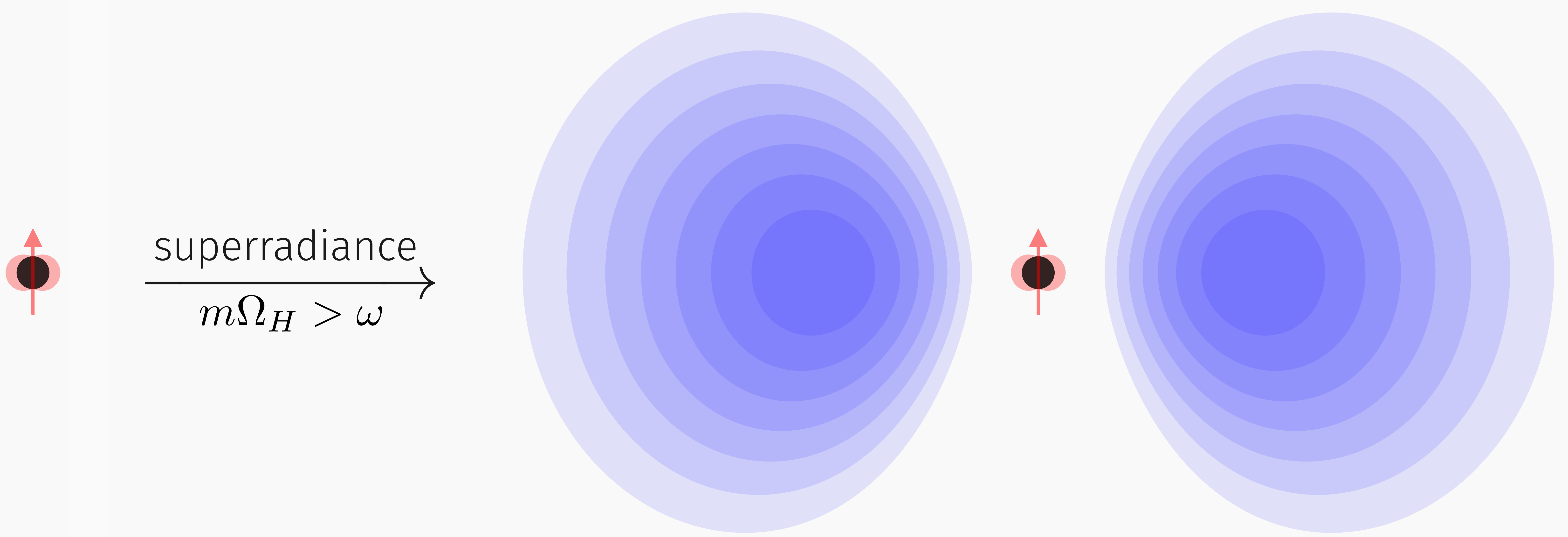
ICTP-AP
International Centre
for Theoretical Physics Asia-Pacific
国际理论物理中心-亚太地区

Black Hole Superradiance of Interacting Multifield

Jun Zhang (张君)
ICTP-AP, University of Chinese Academy of Sciences
in collaboration with Yun-Song Piao & Zhi-Qing Zhu

Axion 2026 @ Qingdao

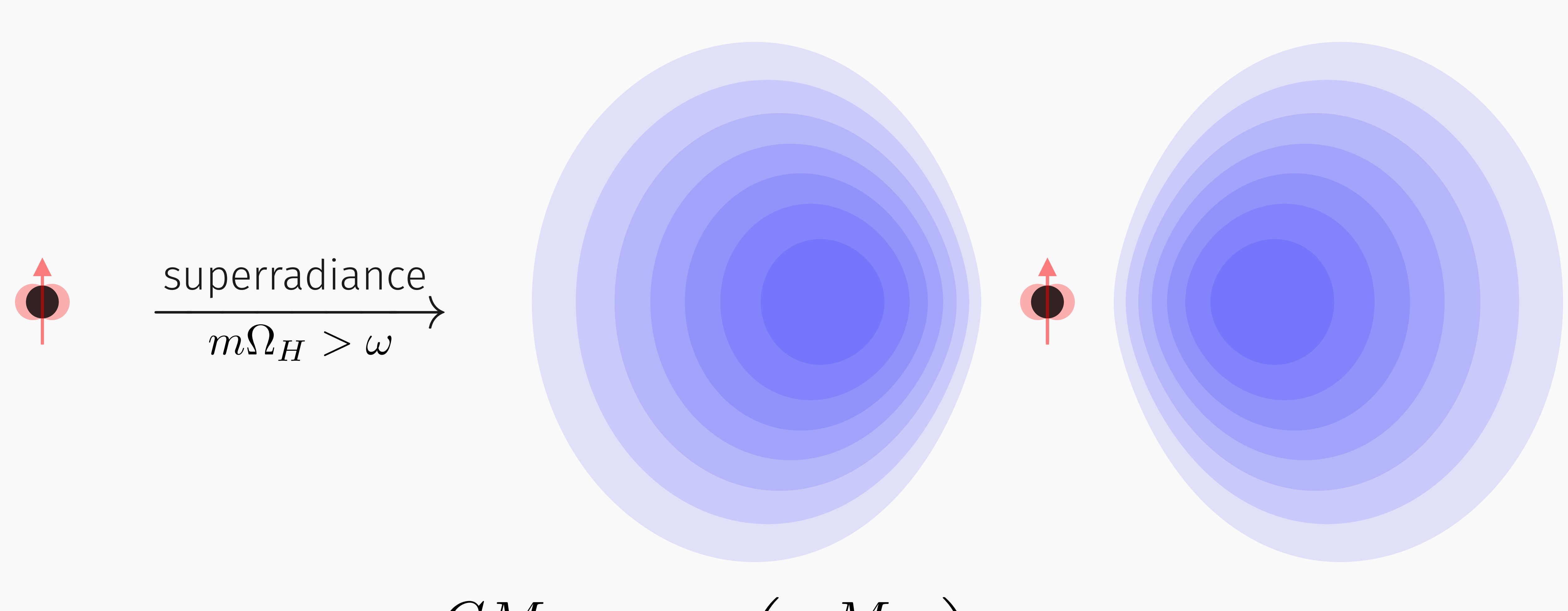
Black Hole Superradiance



$$\alpha \equiv \frac{GM\mu}{\hbar c} \simeq 0.1 \left(\frac{M}{10M_\odot}\right)\left(\frac{\mu}{10^{-12}eV}\right)$$

[Press & Teukolsky 1972, Zouros & Eardley 1979, Detweiler 1980]

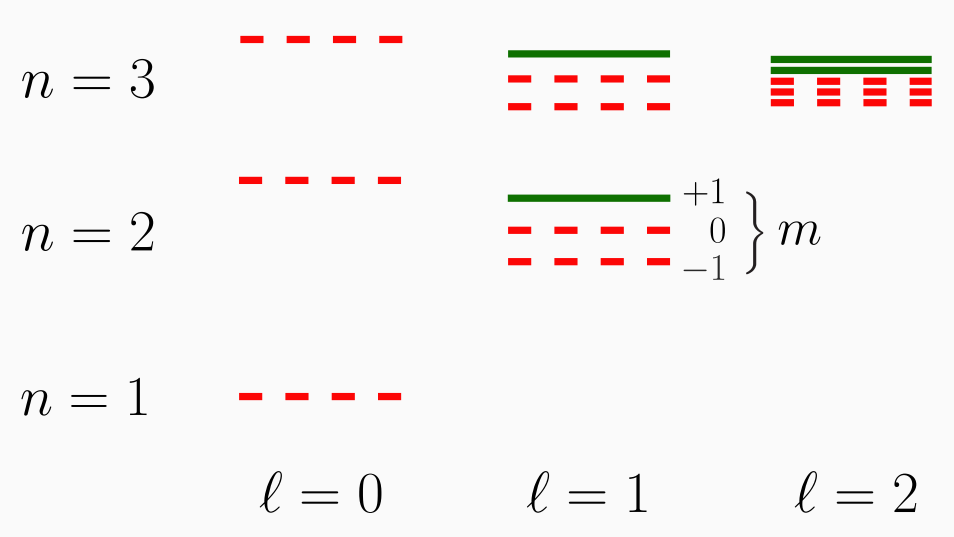
Black Hole Superradiance



$$\alpha \equiv \frac{GM\mu}{\hbar c} \simeq 0.1 \left(\frac{M}{10M_\odot}\right)\left(\frac{\mu}{10^{-12}eV}\right)$$

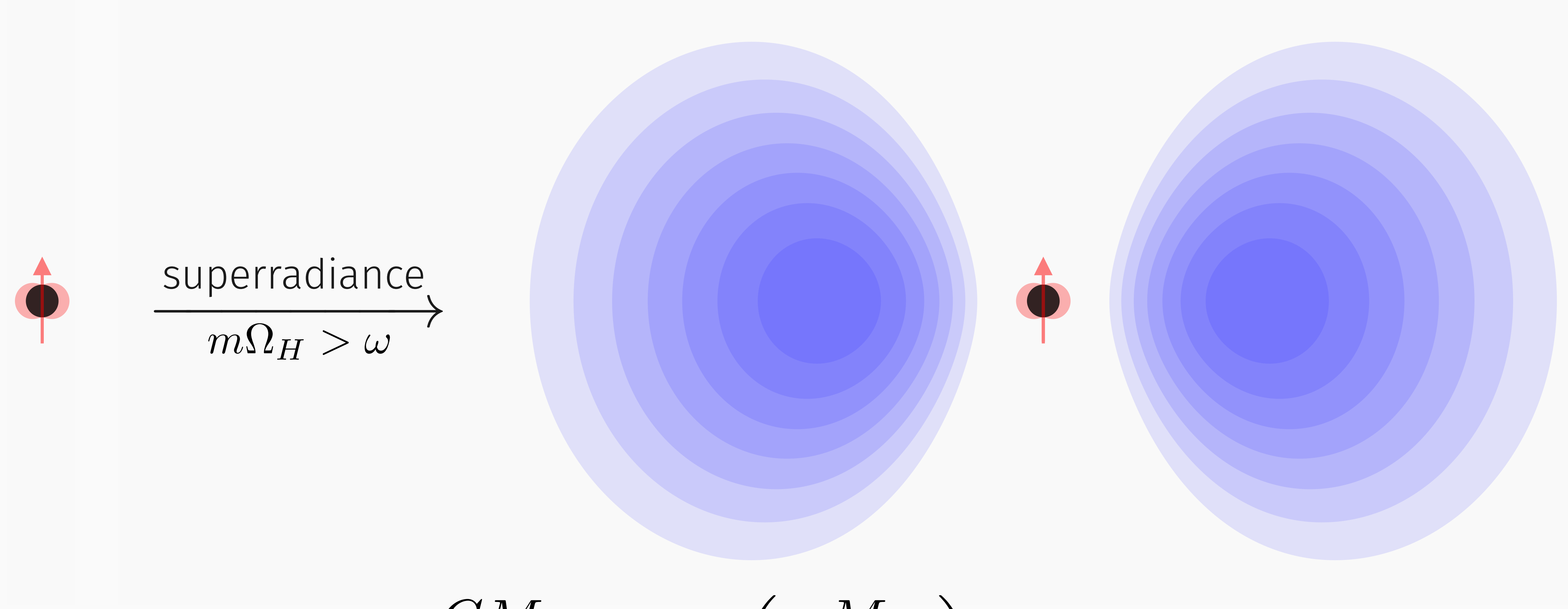
[Press & Teukolsky 1972, Zouros & Eardley 1979, Detweiler 1980]

- Cloud size ~ $r_{\rm B} = GM/\alpha^2$
- Hydrogen atom-like spectrum



- Growth time scale
  ~ 12 days $(0.1/\alpha)^{4\ell+5}\,(M/10M_\odot)$

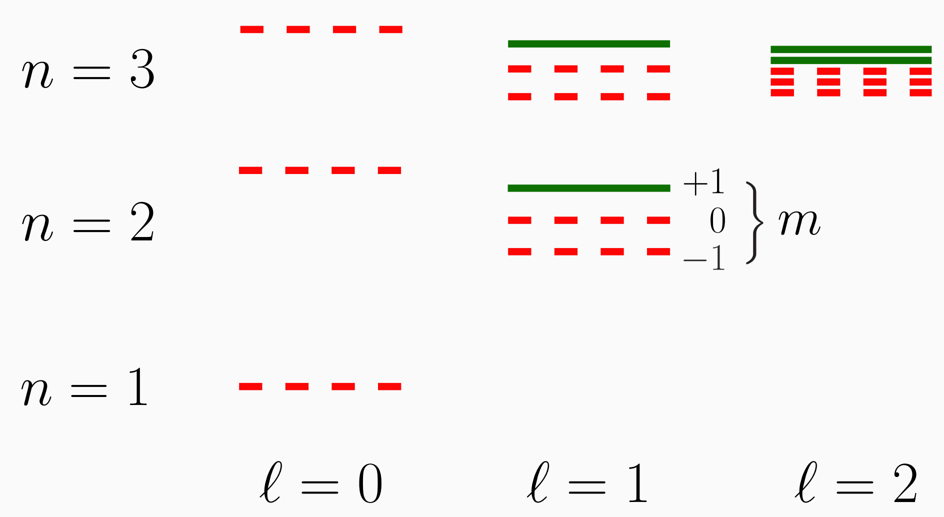
Black Hole Superradiance



$$\alpha \equiv \frac{GM\mu}{\hbar c} \simeq 0.1 \left(\frac{M}{10M_\odot}\right)\left(\frac{\mu}{10^{-12}eV}\right)$$

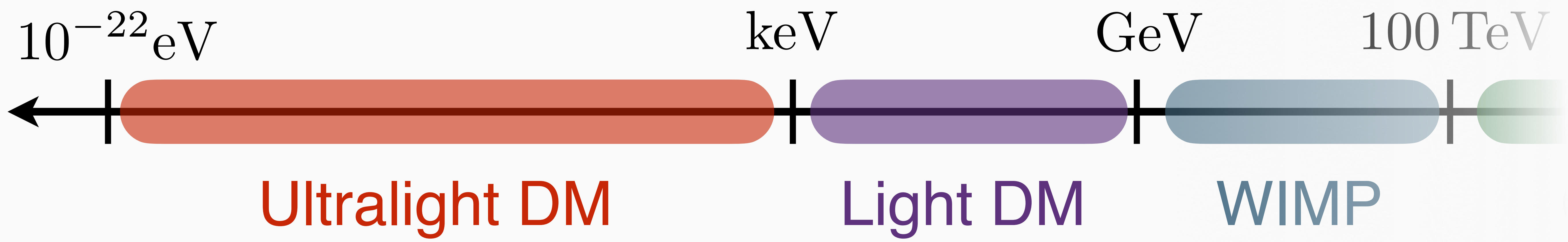
[Press & Teukolsky 1972, Zouros & Eardley 1979, Detweiler 1980]

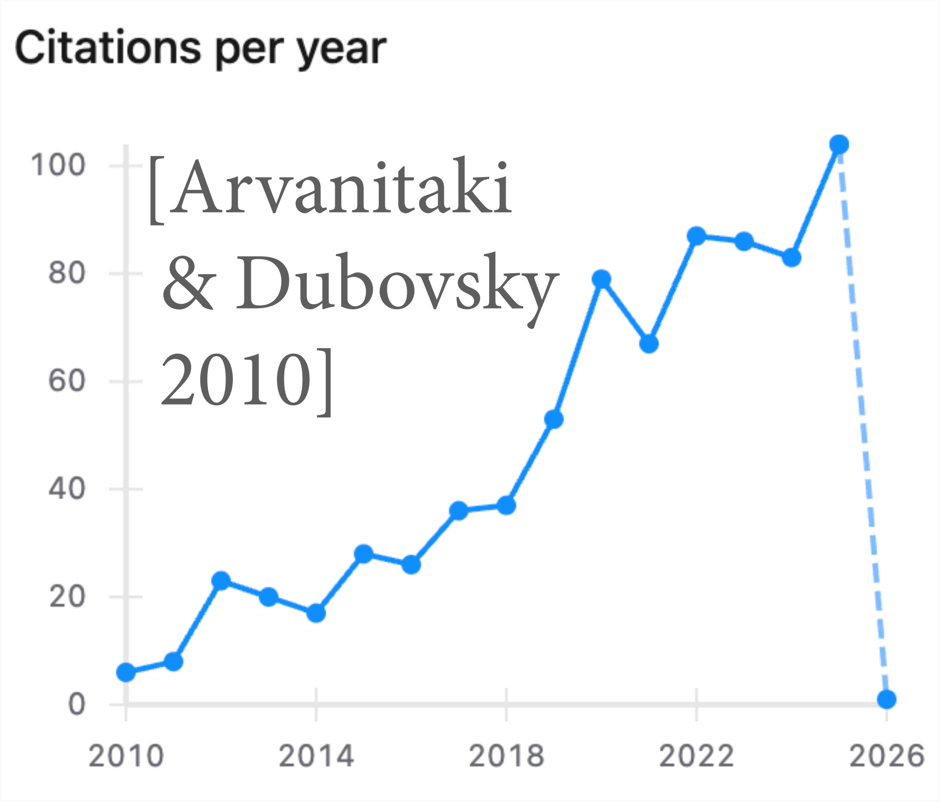
- Cloud size ~ $r_{\rm B} = GM/\alpha^2$
- Hydrogen atom-like spectrum



- Growth time scale
  ~ 12 days $(0.1/\alpha)^{4\ell+5}\,(M/10M_\odot)$

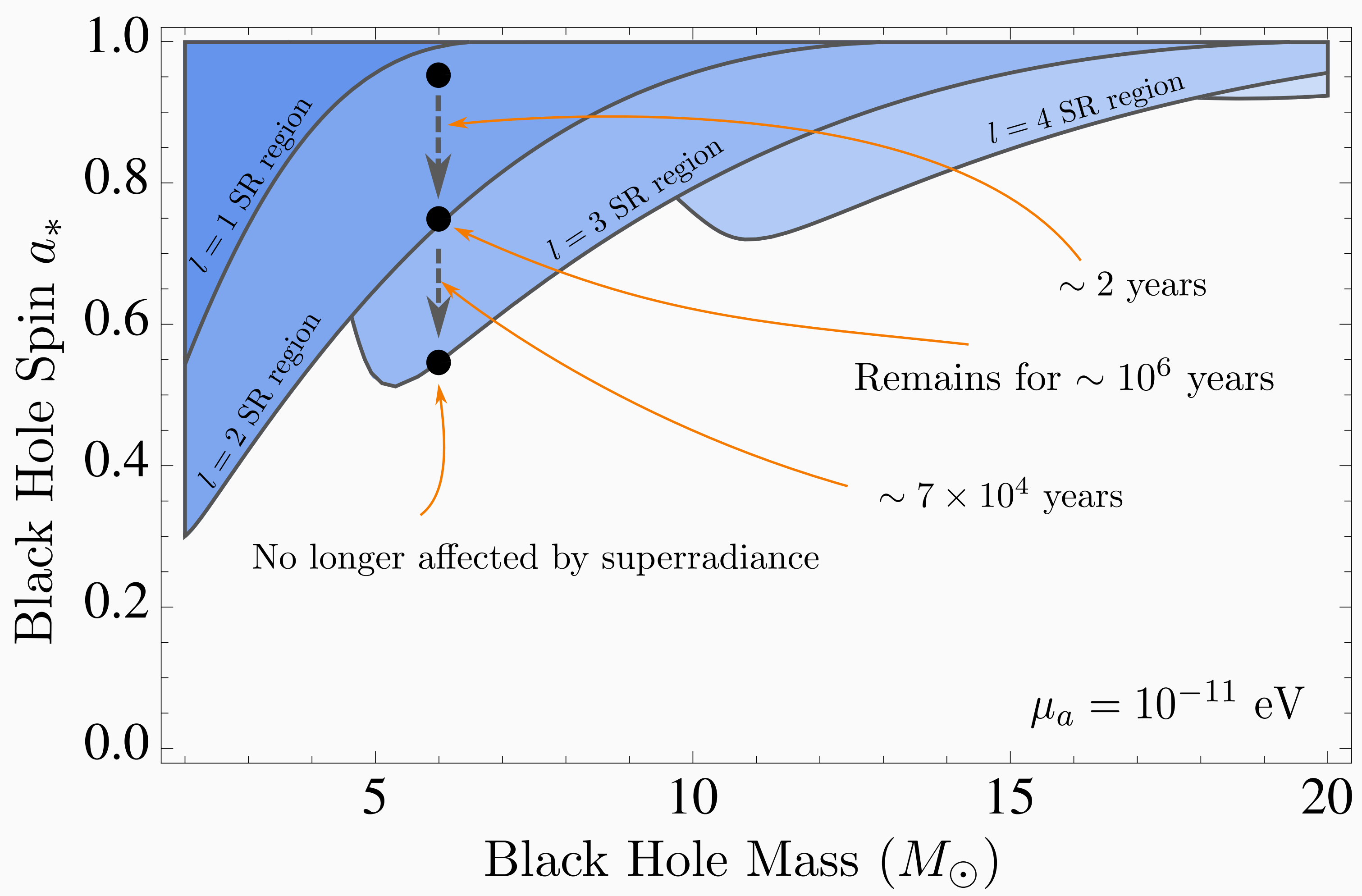
Mass of Dark Matter Particles

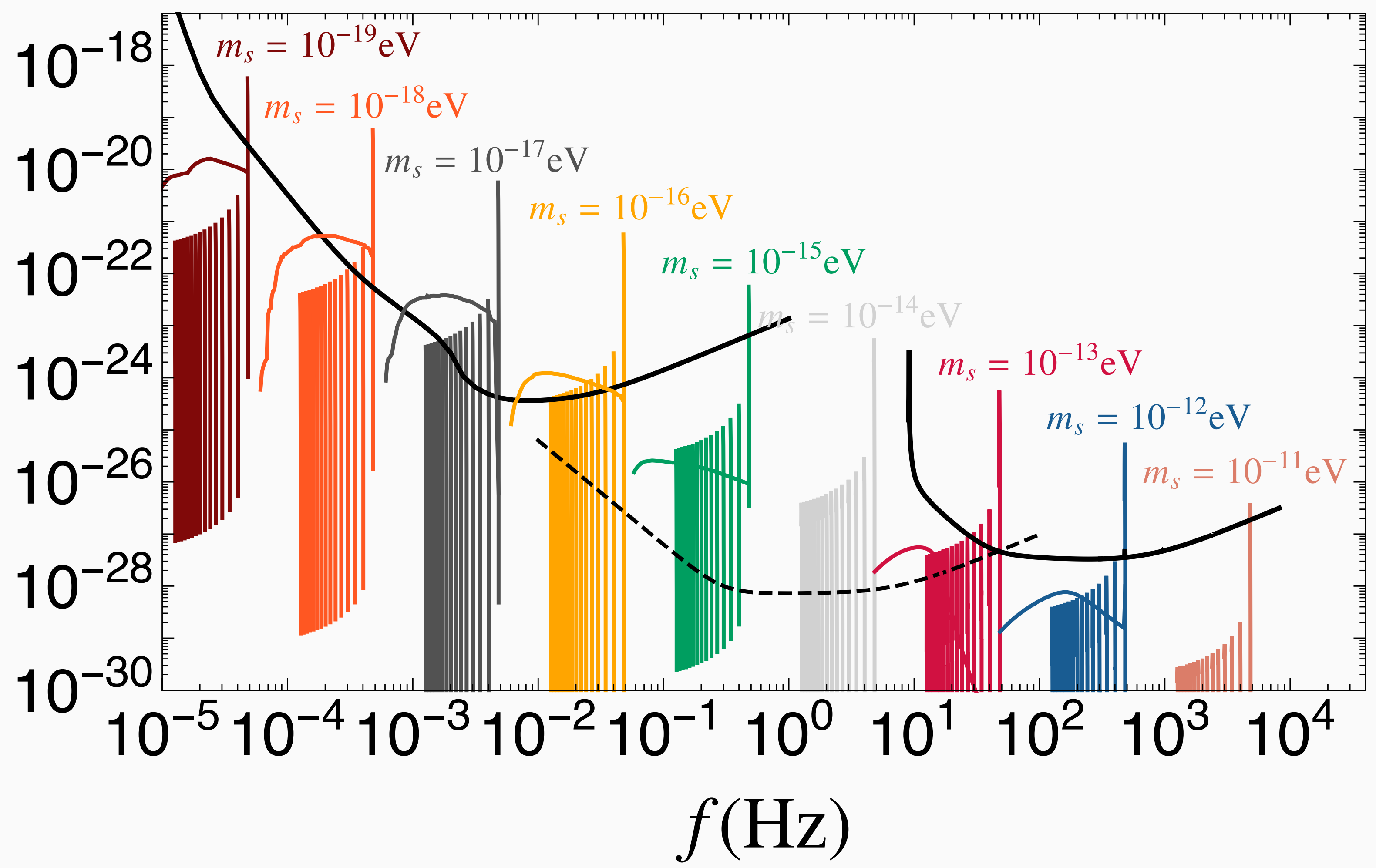


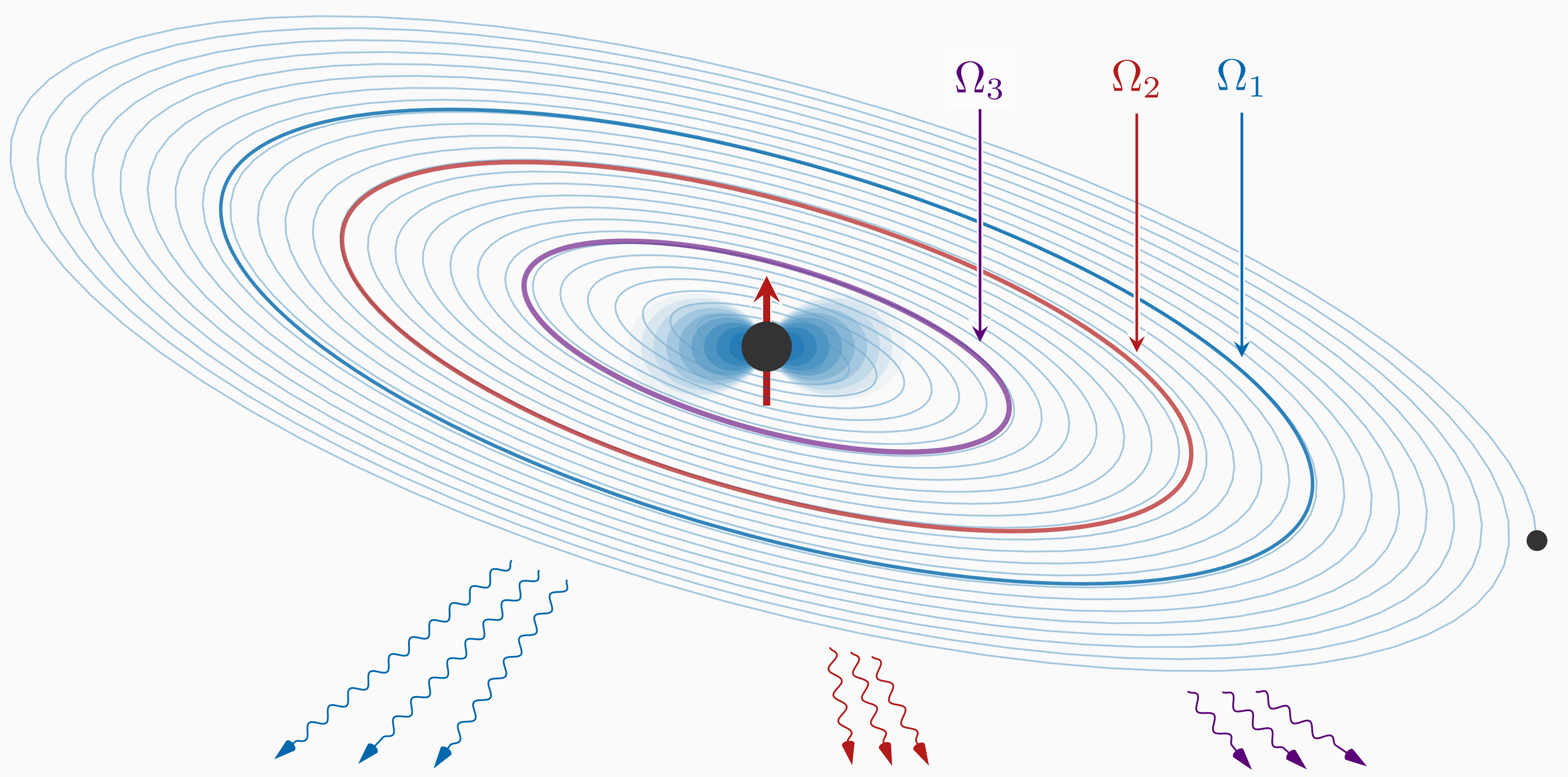


Observational Signatures

- Black hole spindown
- GWs emitted by superradiant clouds
- Dynamical signatures of superradiant cloud in black hole binaries
- More signatures with couplings to the SM particles …







Constraints - BH Spin Down

GW231123

$$M_1 = 137^{+0.22}_{-0.17} M_\odot$$

$$M_2 = 103^{+0.20}_{-0.52} M_\odot$$

$$\chi_1 = 0.9^{+0.10}_{-0.19}$$

$$\chi_2 = 0.8^{+0.20}_{-0.51}$$

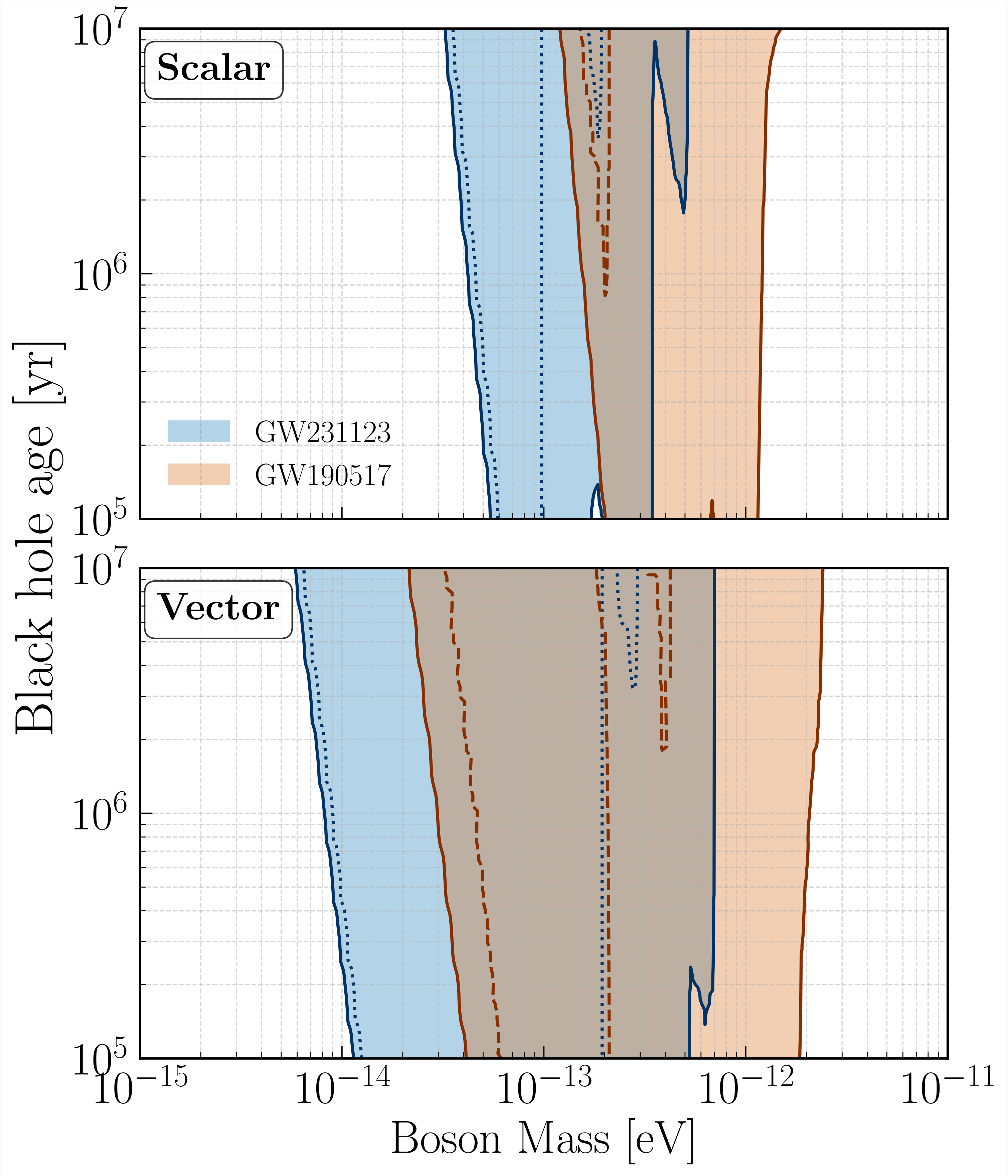
GW190517

$$M_1 = 39.2^{+13.9}_{-9.2} M_\odot$$

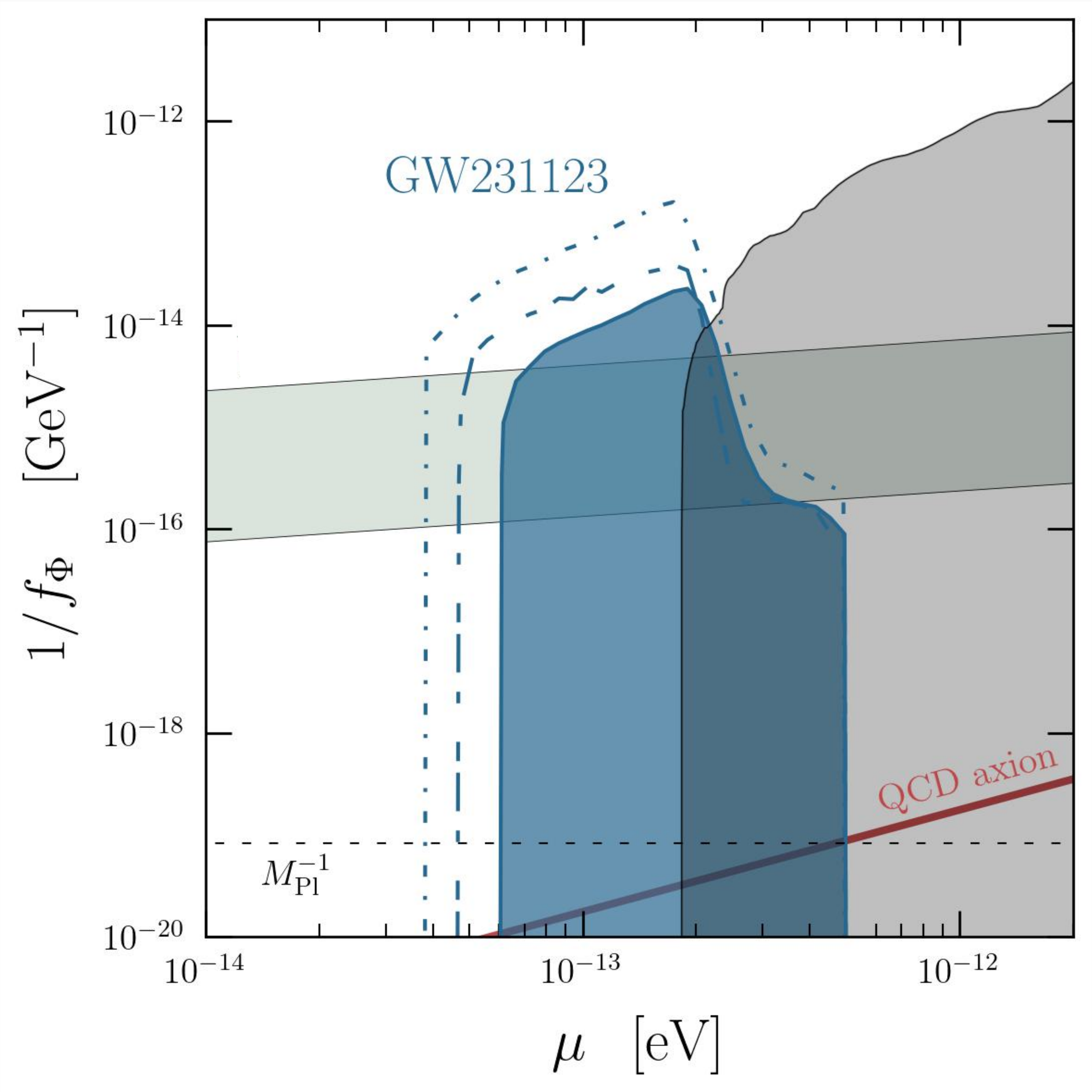
$$M_2 = 24.0^{+7.4}_{-7.9} M_\odot$$

$$\chi_1 = 0.9^{+0.09}_{-0.30}$$

$$\chi_2 = 0.8^{+0.34}_{-0.54}$$



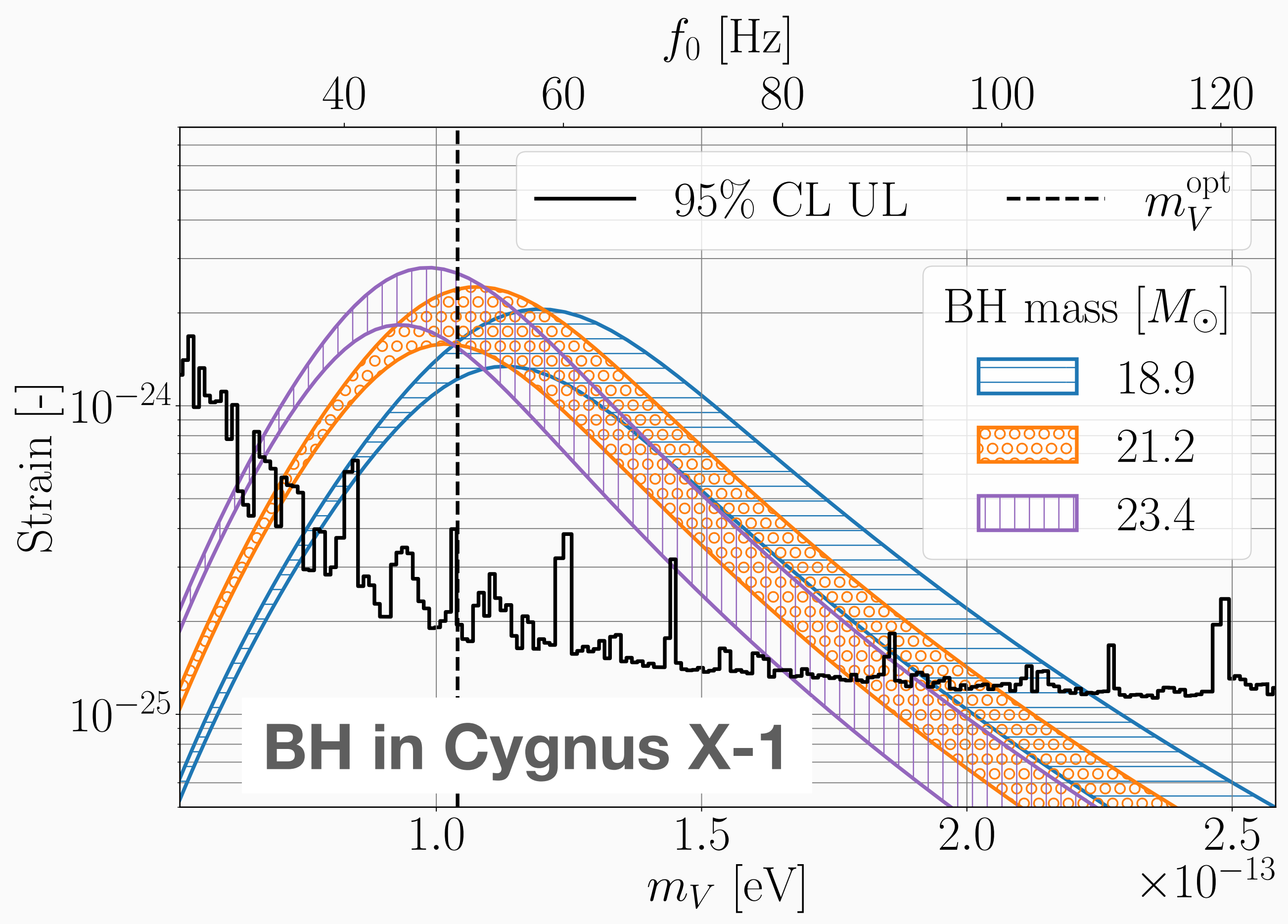
[East et al., arXiv:2507.20979]

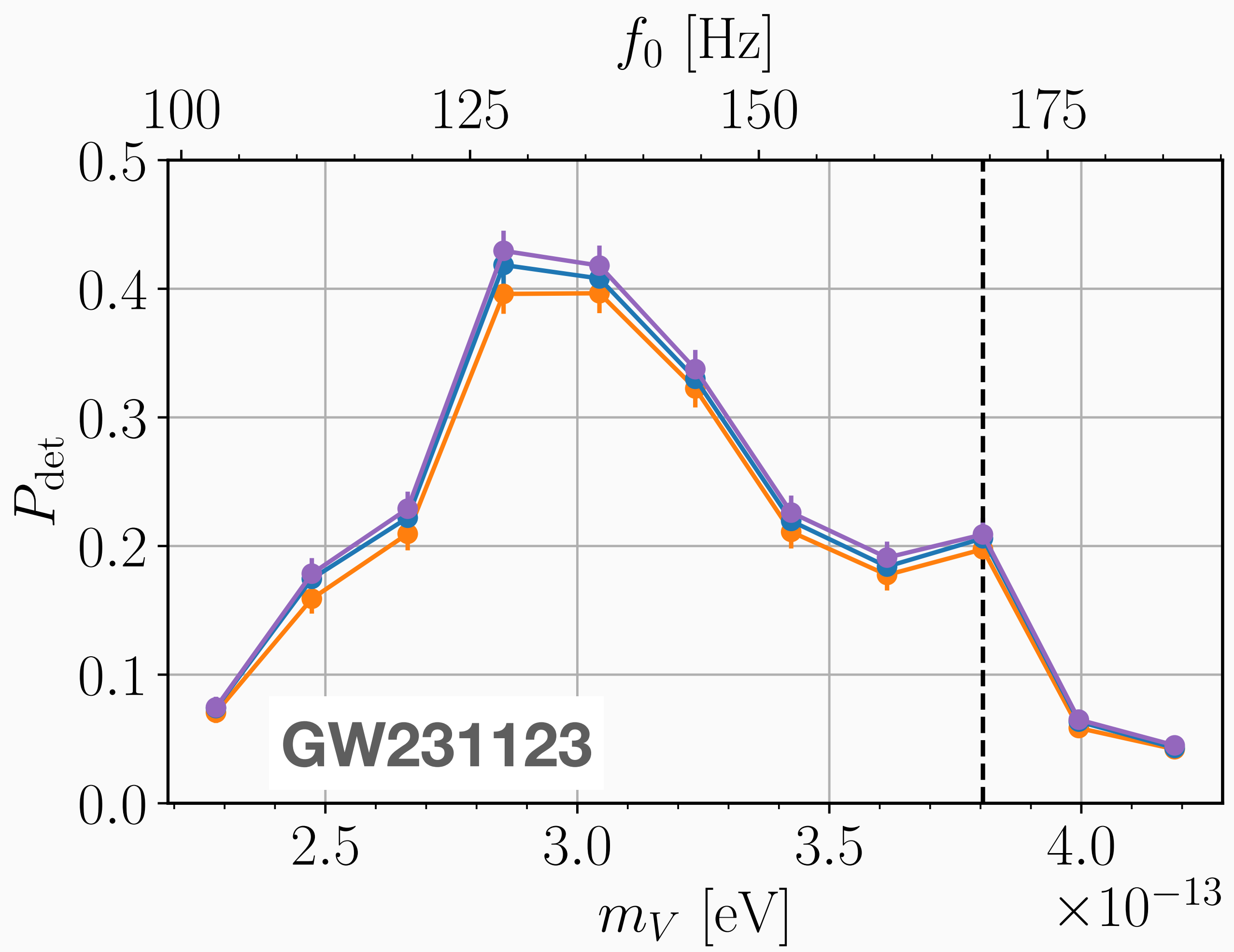


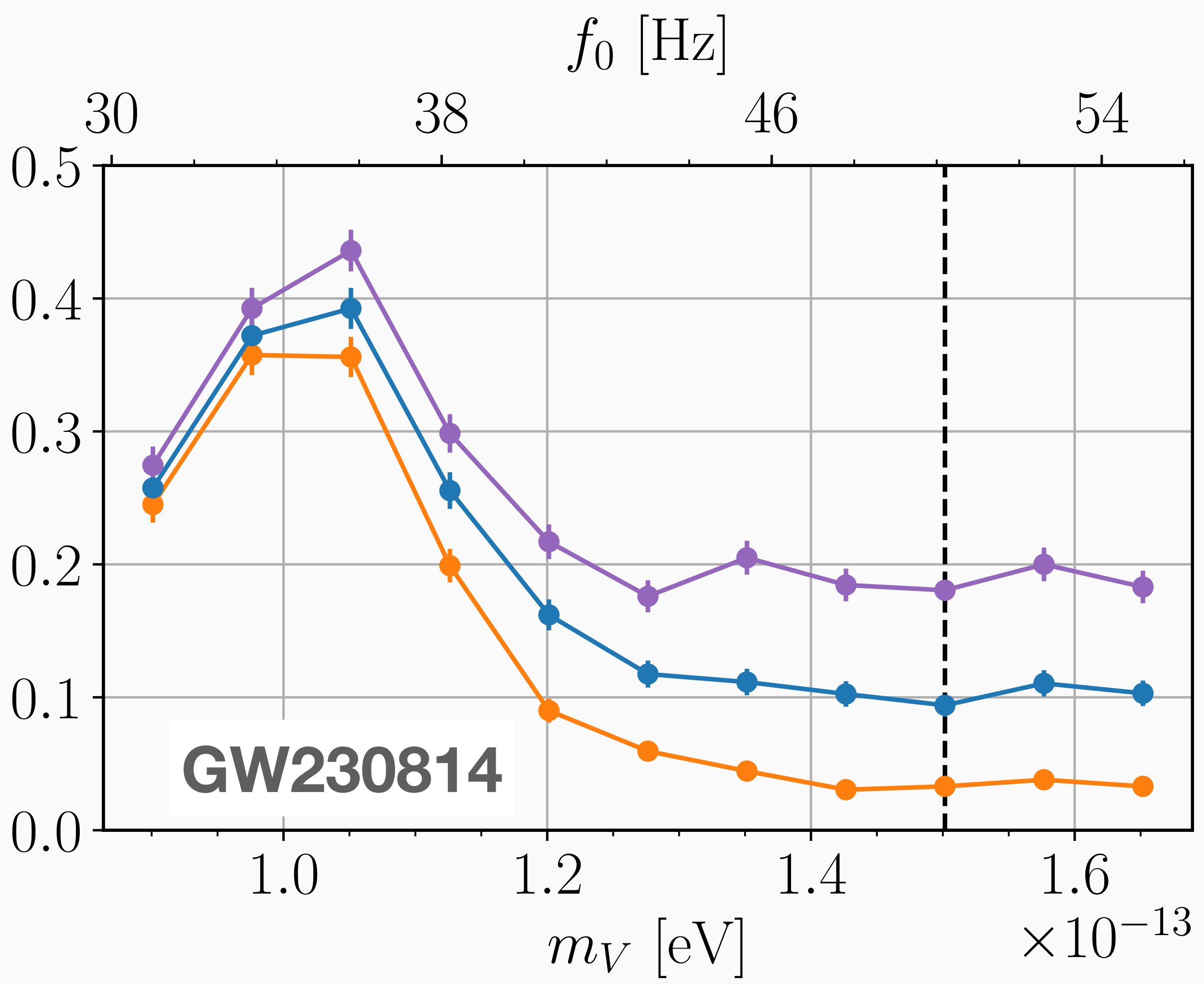
[Caputo et al., arXiv:2507.21788]

Constraints - GWs

- Directed searches on target sources [LVK, arXiv:2509.07352]

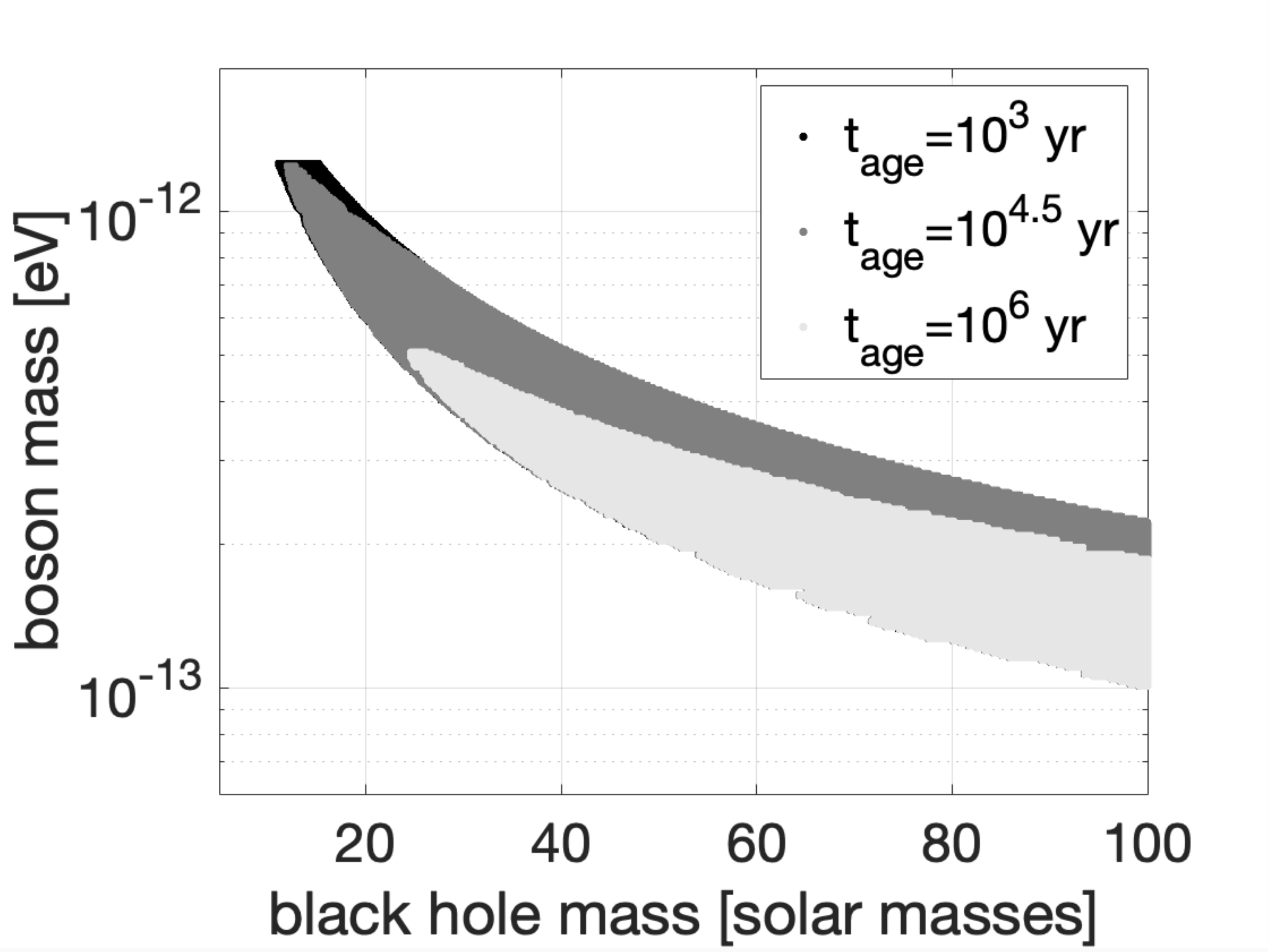


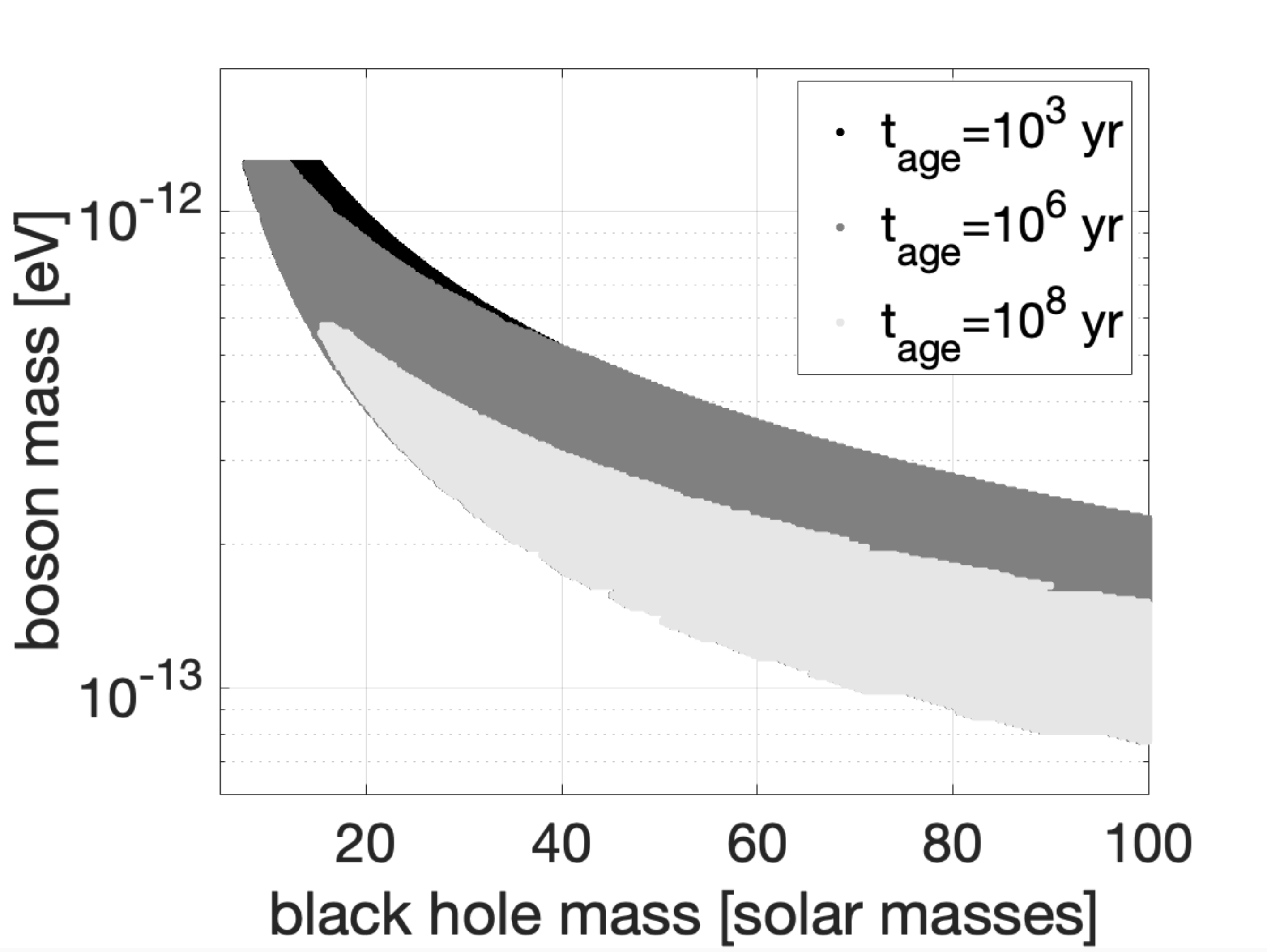




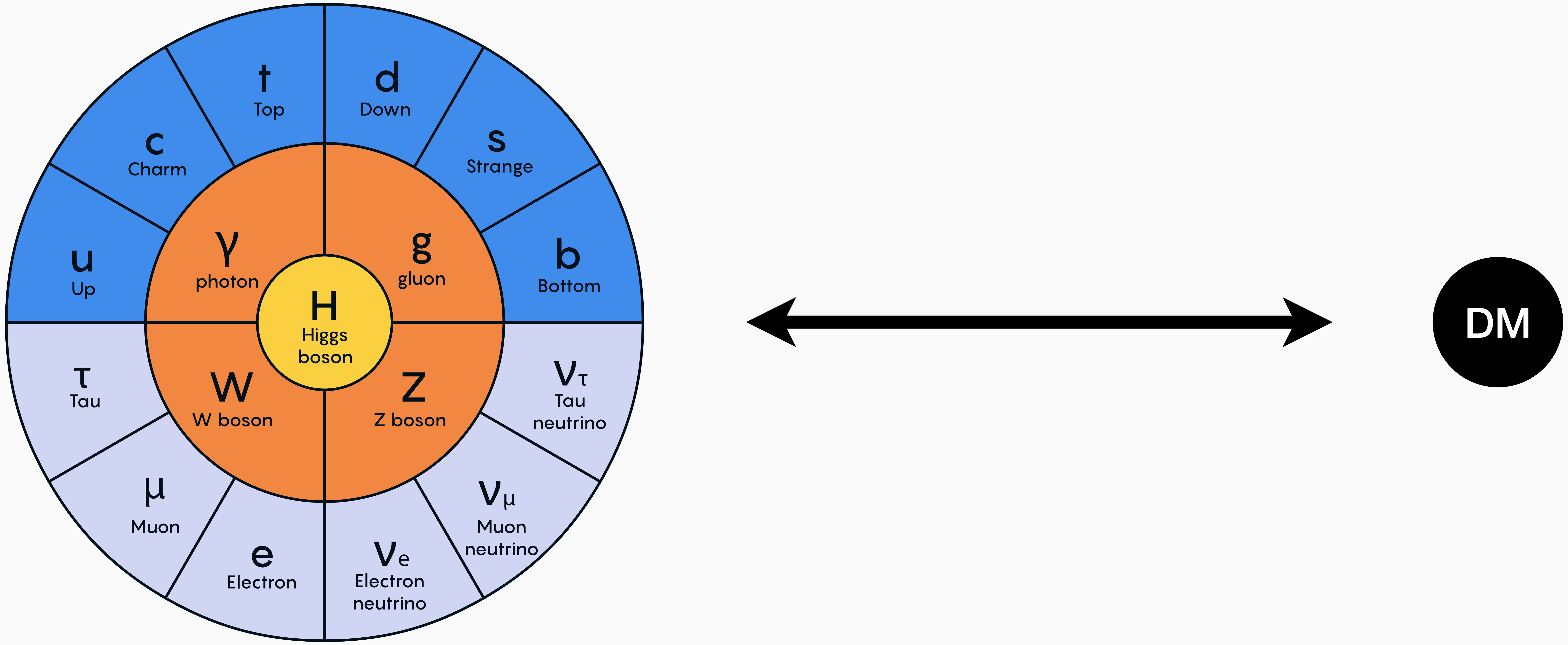
- All sky searches

[LVK, PRD (2022)]

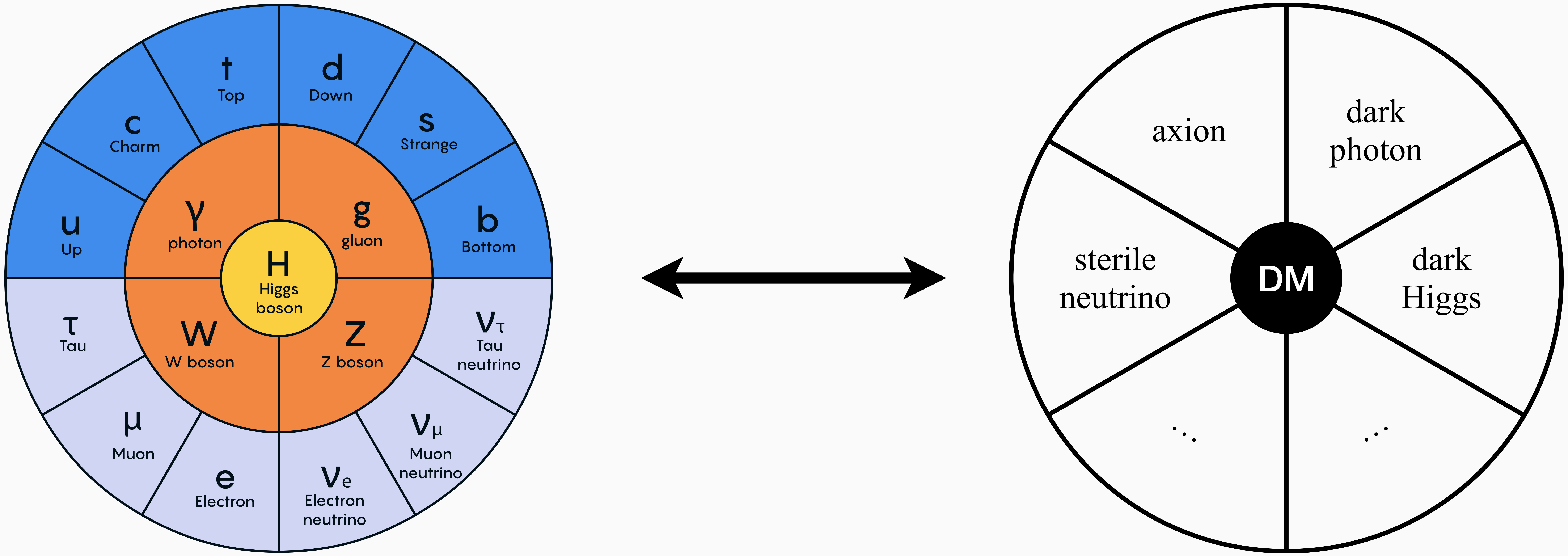




Why Multiple Fields



Why Multiple Fields



SR with Two Interacting Fields

Model

$$\mathcal{L} = -\frac{1}{2}g^{ab}\partial_a\psi\,\partial_b\psi - \frac{1}{2}\mu^2\psi^2 - \frac{1}{2}g^{ab}\partial_a\varphi\,\partial_b\varphi - \frac{1}{2}\nu^2\varphi^2 + \mathcal{L}_{\text{int}} \qquad \mathcal{L}_{\text{int}} = \lambda\psi^2\,\varphi + \lambda'\psi\,\varphi^2$$

SR with Two Interacting Fields

Model

$$\mathcal{L} = -\frac{1}{2} g^{ab} \partial_a \psi \, \partial_b \psi - \frac{1}{2} \mu^2 \psi^2 - \frac{1}{2} g^{ab} \partial_a \varphi \, \partial_b \varphi - \frac{1}{2} \nu^2 \varphi^2 + \lambda \psi^2 \, \varphi$$

SR with Two Interacting Fields

Model

$$\mathcal{L} = -\frac{1}{2}g^{ab}\partial_a\psi\,\partial_b\psi - \frac{1}{2}\mu^2\psi^2 - \frac{1}{2}g^{ab}\partial_a\varphi\,\partial_b\varphi - \frac{1}{2}\nu^2\varphi^2 + \lambda\psi^2\,\varphi$$

$$\left(\Box - \mu^2\right)\psi = -2\lambda\psi\varphi \qquad \left(\Box - \nu^2\right)\varphi = -\lambda\psi^2$$

- Corrections on $\mathrm{Im}\,\omega_{211}$ via the perturbative approach

$\mathcal{O}(\lambda^0)$ $$\left(\Box - \mu^2\right)\psi = 0 \qquad \psi = \bar{\psi}_{211}$$

$\mathcal{O}(\lambda^1)$

$$\int \mathrm{d}^3\mathbf{r}\,\bar{\psi}^*_{n\ell m}\times \left(\Box - \mu^2\right)\psi = -2\lambda\bar{\psi}_{211}\varphi$$

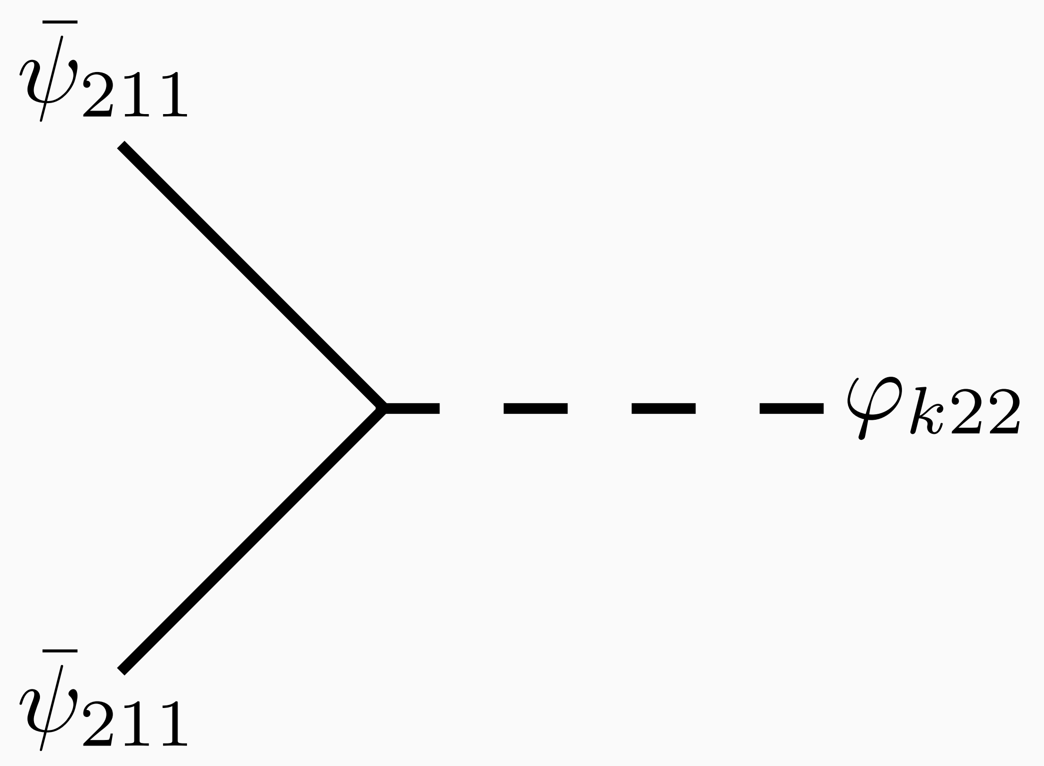
$$\int \mathrm{d}^3\mathbf{r}\,\varphi^*_{n\ell m}\times \left(\Box - \nu^2\right)\varphi = -\lambda\bar{\psi}_{211}\psi$$

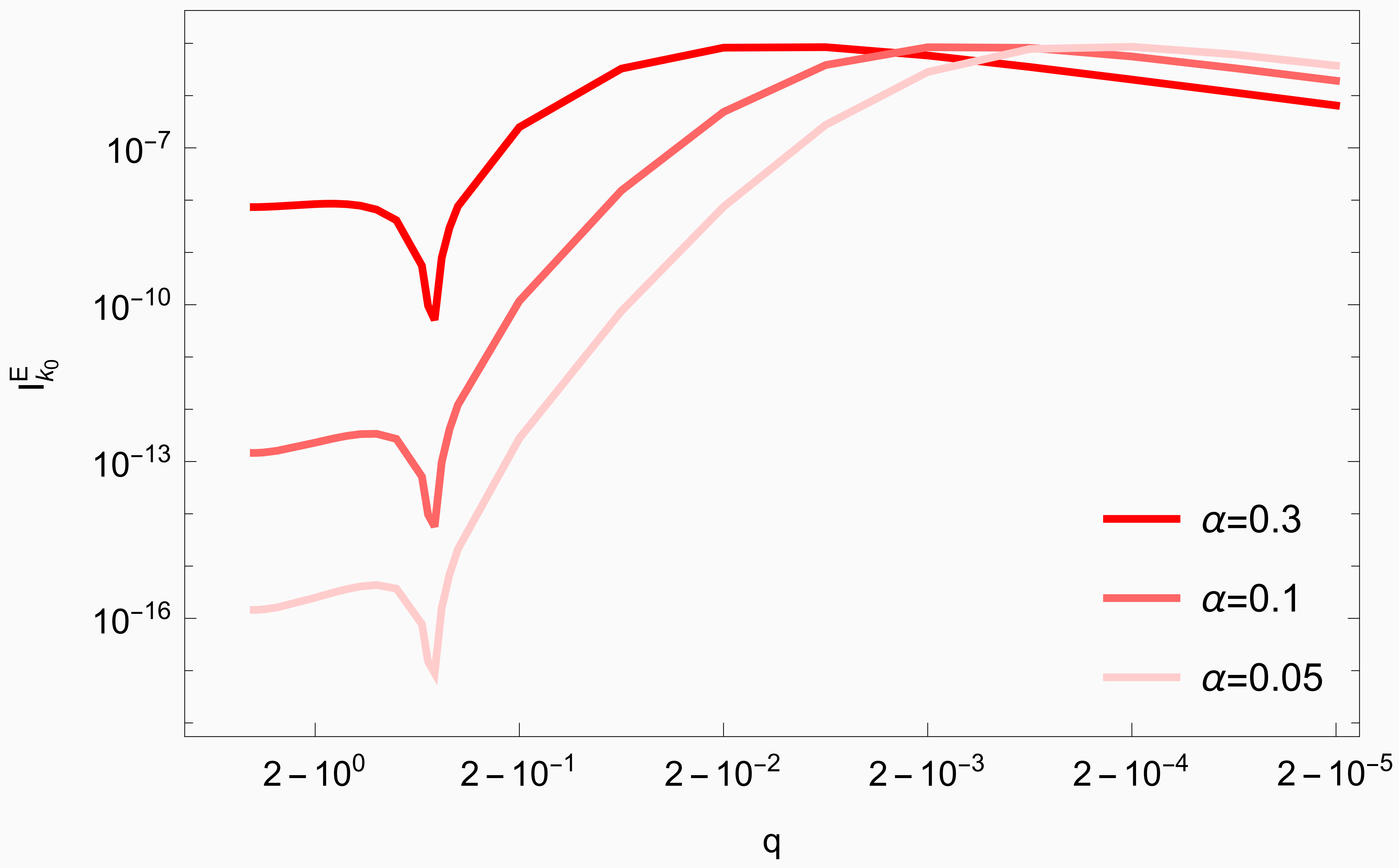
$$\longrightarrow \quad \delta\omega_{211}$$

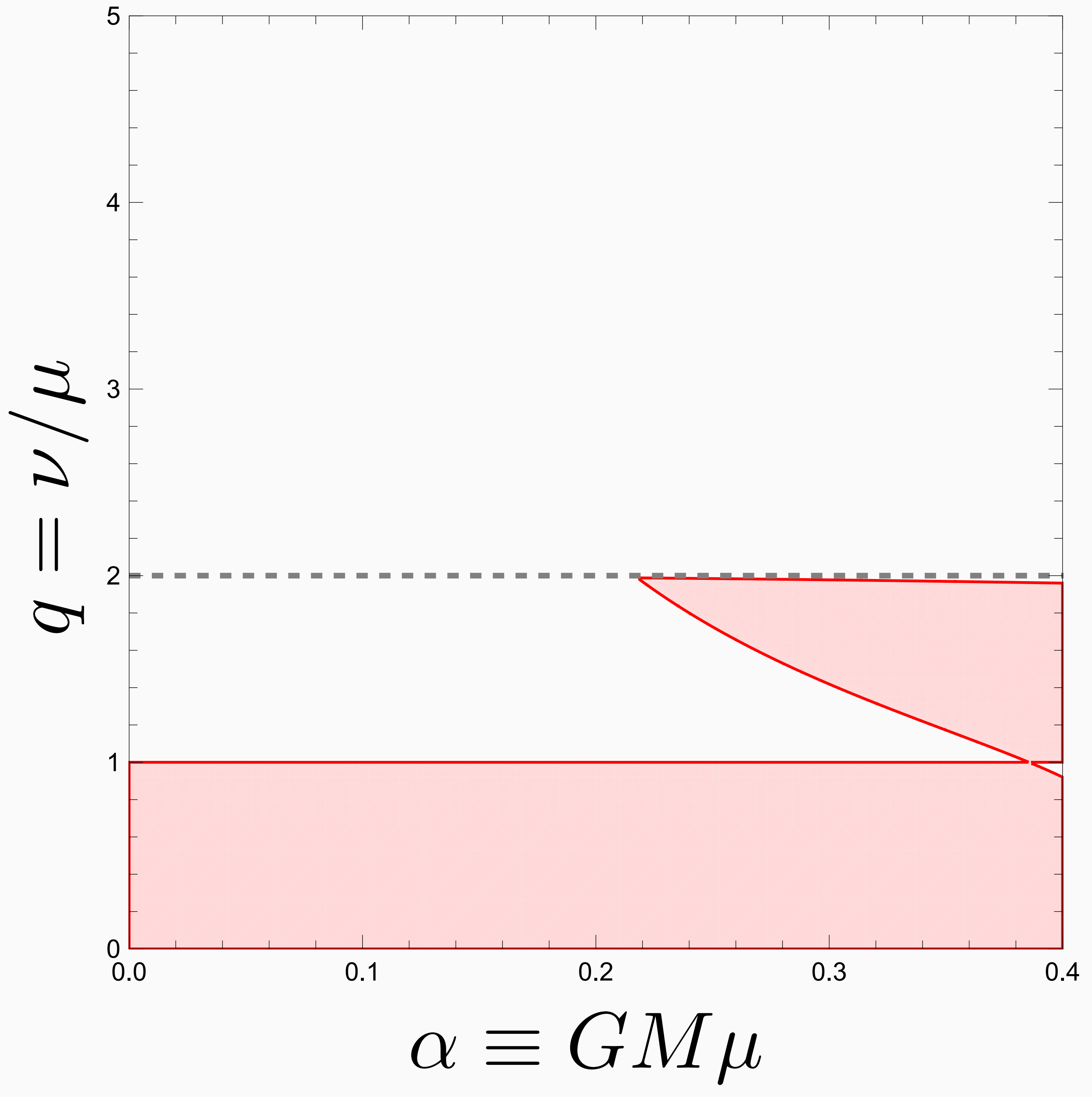
SR with Two Interacting Fields

- Interaction with exited states

$$\mathrm{Im}\delta\omega^{sE}_{211} \simeq -\bar{\lambda}^2 N_0 \frac{\mu\alpha^2}{2\sqrt{4-q^2}} \mathrm{I}^E_{k_0}(q,\alpha)$$



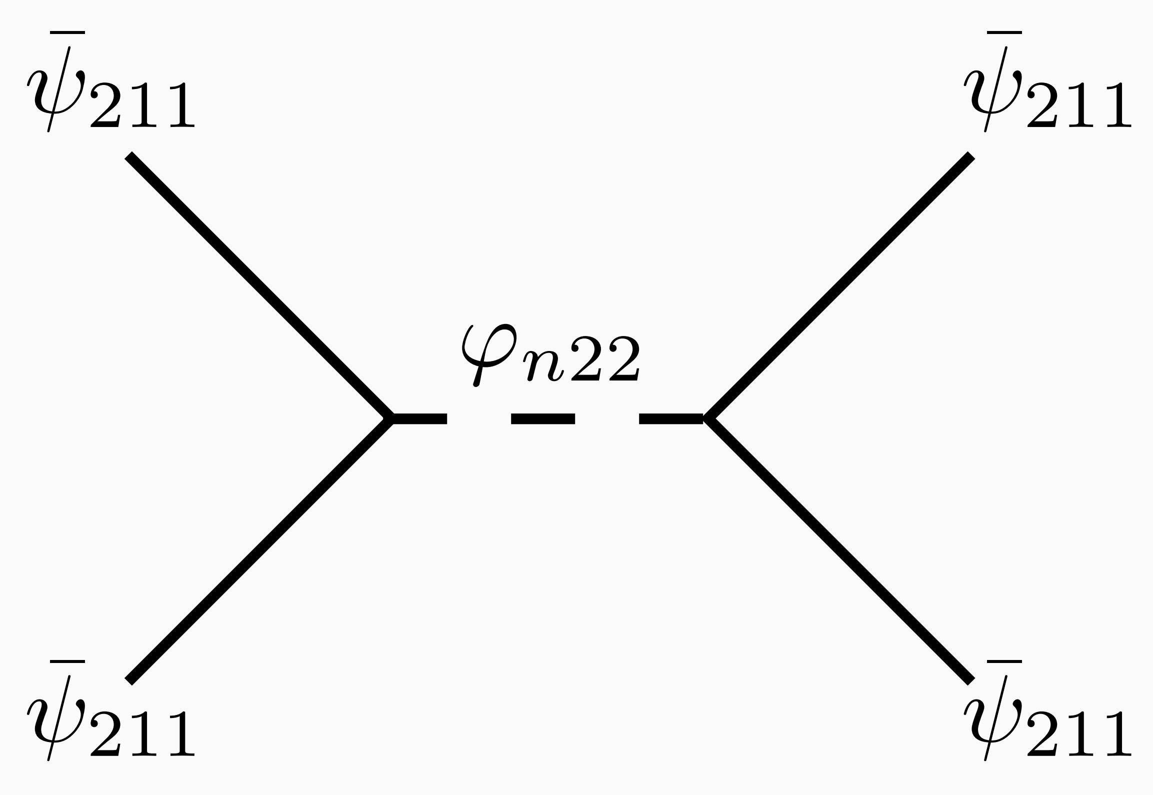


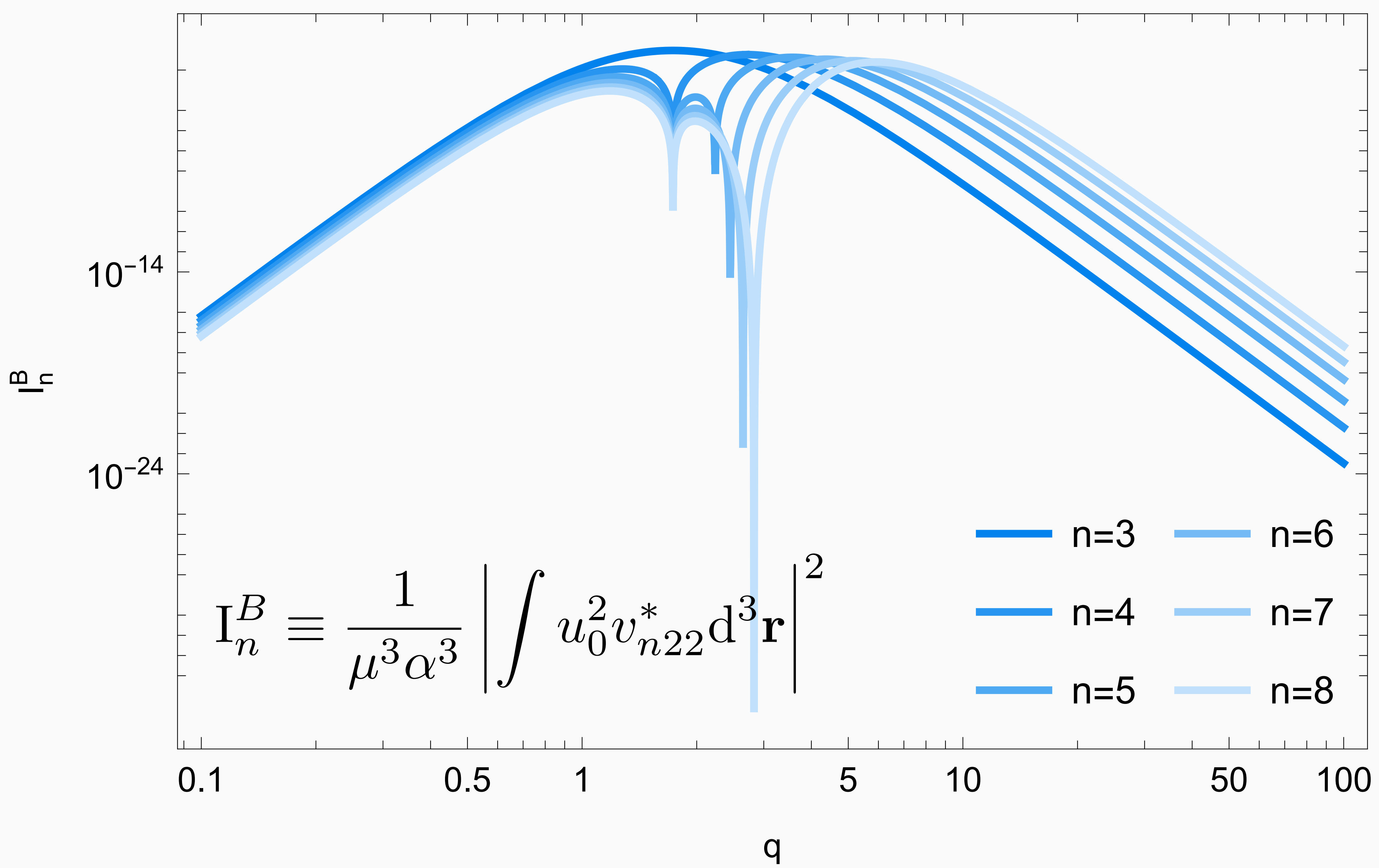


SR with Two Interacting Fields

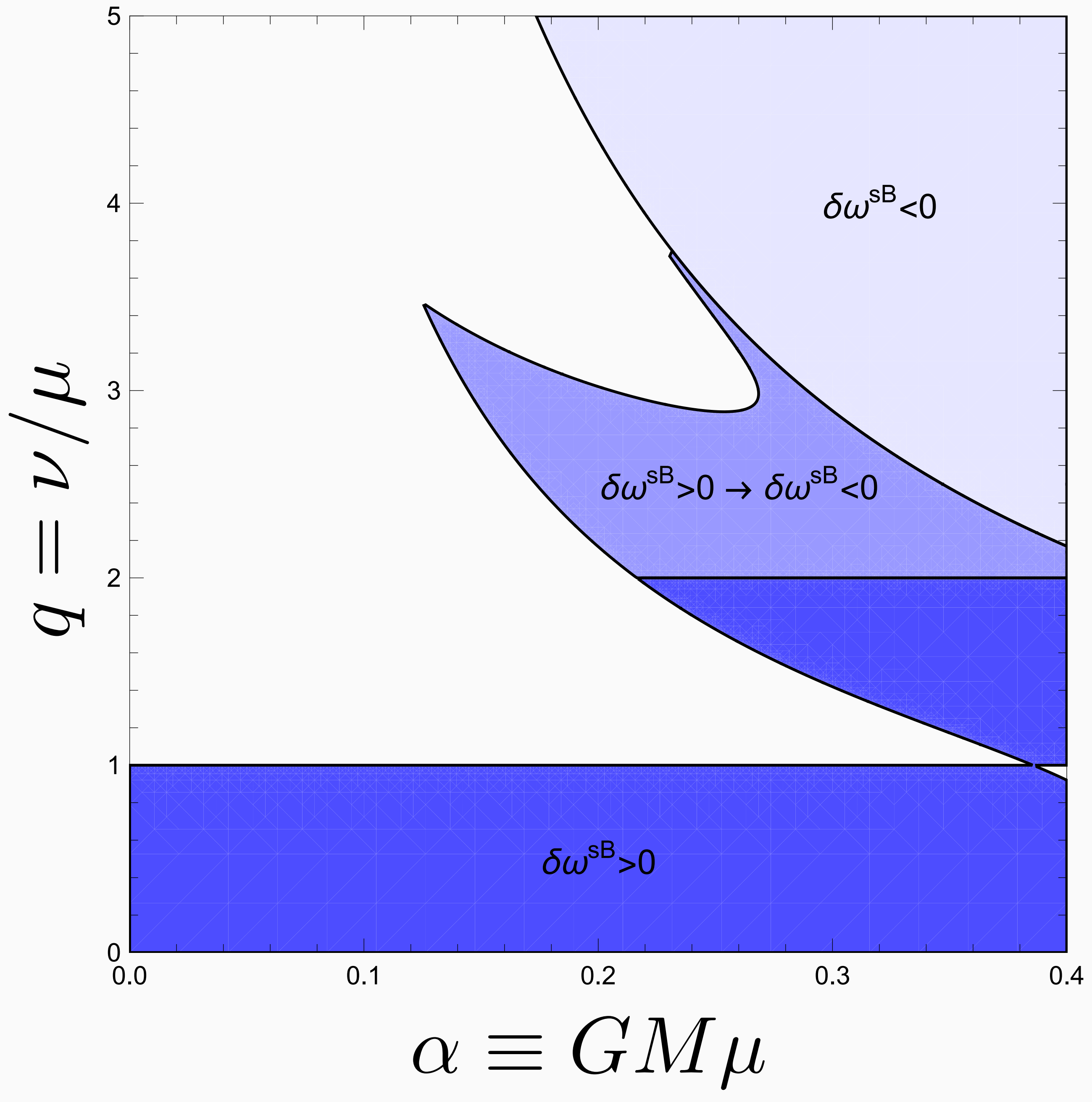
- Interaction with bound states

$$\mathrm{Im}\delta\omega_{211}^{sB} \simeq \alpha^3\bar{\lambda}^2 N_0 \frac{4q^2\mu}{(q^2-4)^2}\sum_{n\geq 3}\frac{\mathrm{Im}\sigma_n}{\nu}\mathrm{I}_n^B(q)$$





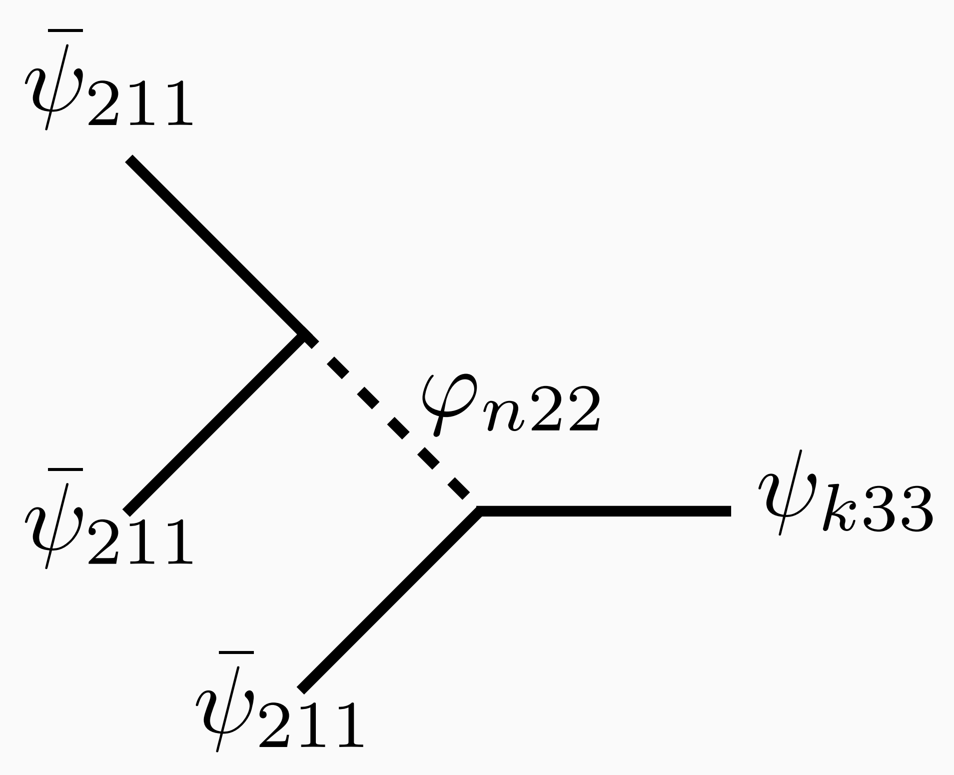
$$\mathrm{I}_n^B \equiv \frac{1}{\mu^3\alpha^3}\left|\int u_0^2 v_{n22}^* \mathrm{d}^3\mathbf{r}\right|^2$$

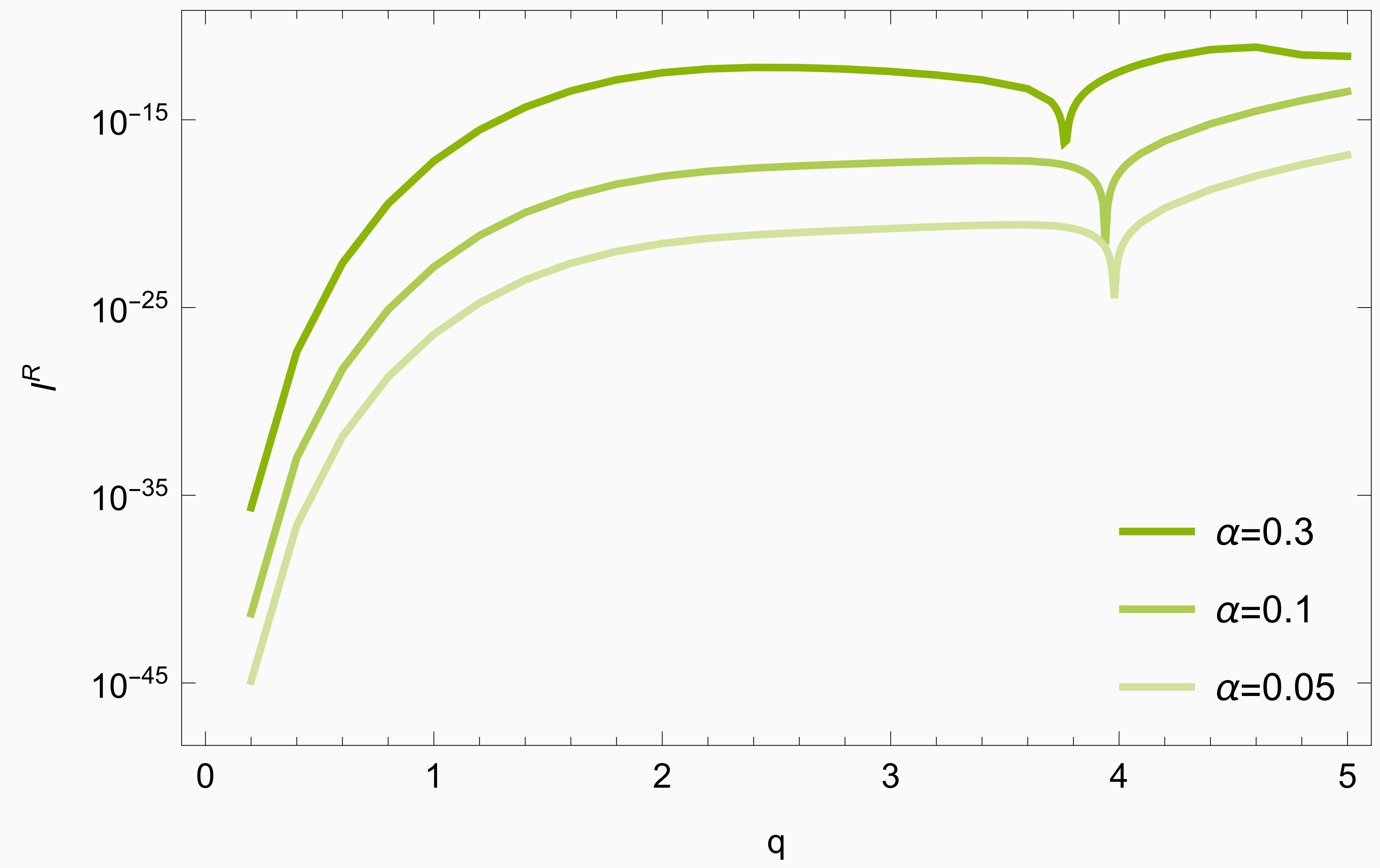


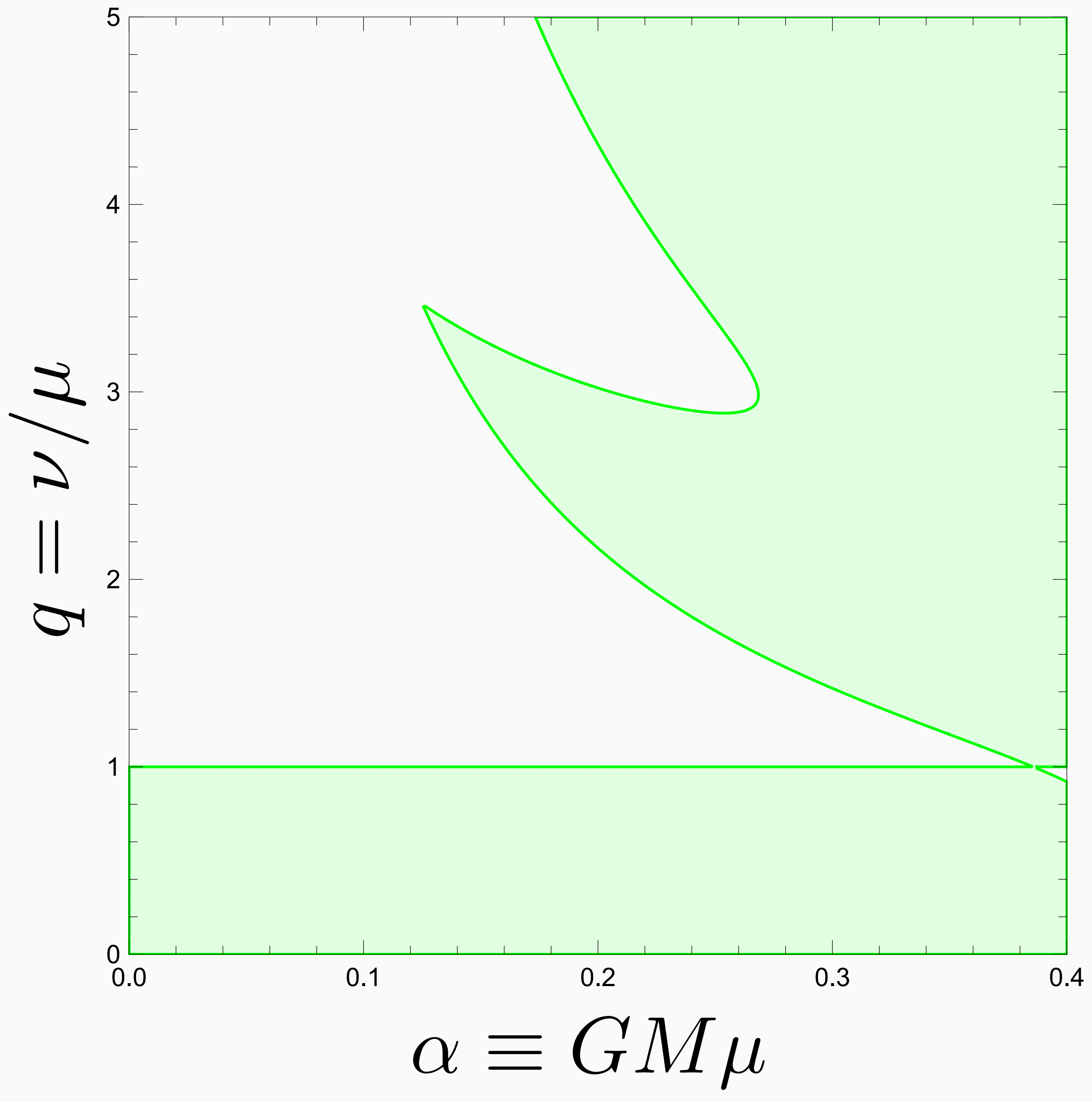
SR with Two Interacting Fields

- $3\,\psi$ radiation

$$\Gamma_R \equiv \frac{P}{\omega_R N_0} \simeq \sqrt{2}\mu N_0^2 \bar{\lambda}^4 \alpha^5 \mathrm{I}_R(\alpha, q)$$





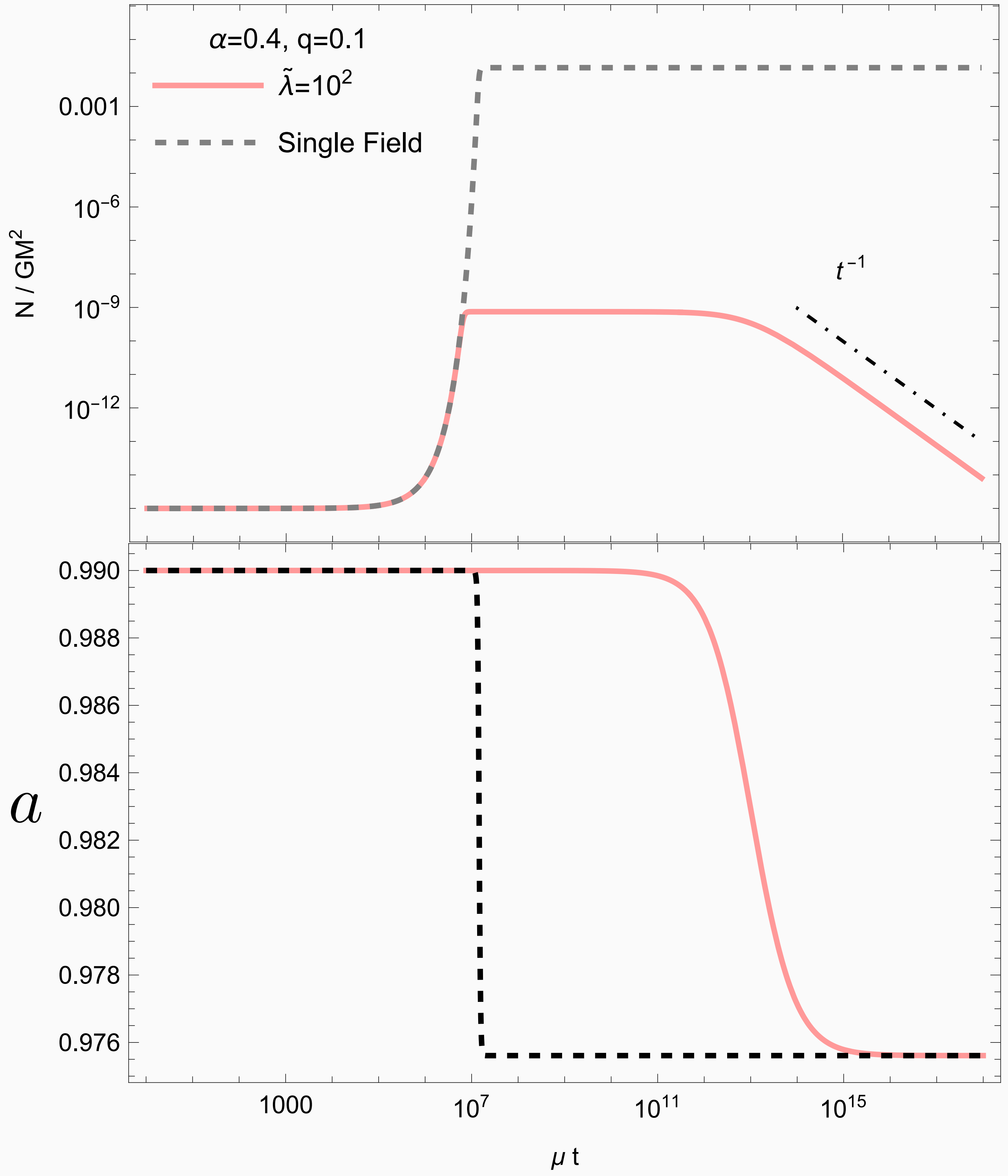


SR with Two Interacting Fields

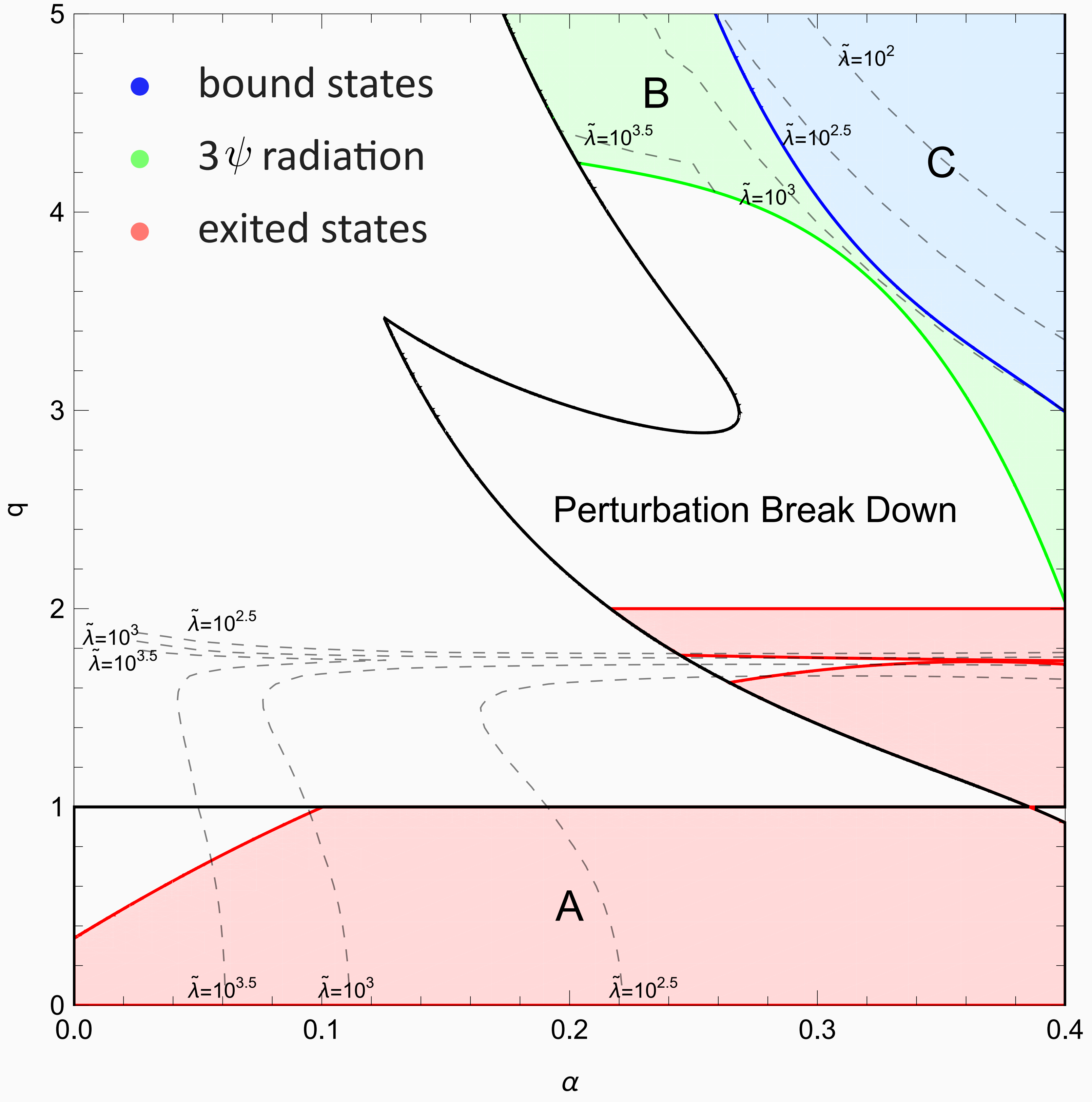
Superradiance evolution

$$\dot{\epsilon}_{211} = \gamma_{211}\epsilon_{211} - (\gamma_B + \gamma_E)\,\epsilon_{211}^2 - \gamma_R\epsilon_{211}^3$$

$$\dot{a} = -\gamma_{211}\epsilon_{211} + \gamma_B\epsilon_{211}^2$$



$$\dot{\epsilon}_{211} = 0 \longrightarrow \epsilon_{eq}$$



$$\lambda = \frac{\tilde{\lambda}}{\sqrt{GM^2}}\mu \approx \left(\frac{\tilde{\lambda}}{2.7\times10^{38}}\right)\left(\frac{3M_\odot}{M}\right)\mu$$

SR with Two Interacting Fields

Superradiance evolution

$$\dot{\epsilon}_{211} = \gamma_{211}\epsilon_{211} - (\gamma_B + \boxed{\gamma_E})\,\epsilon_{211}^2 - \gamma_R\epsilon_{211}^3$$

$$\dot{a} = -\gamma_{211}\epsilon_{211} + \gamma_B\epsilon_{211}^2$$

- Interaction with exited states

$$\epsilon_{211}' \simeq (\epsilon_{eq} - \epsilon_{211})\epsilon_{211} \qquad \epsilon_{eq} \equiv \gamma_{211}/\gamma_E$$

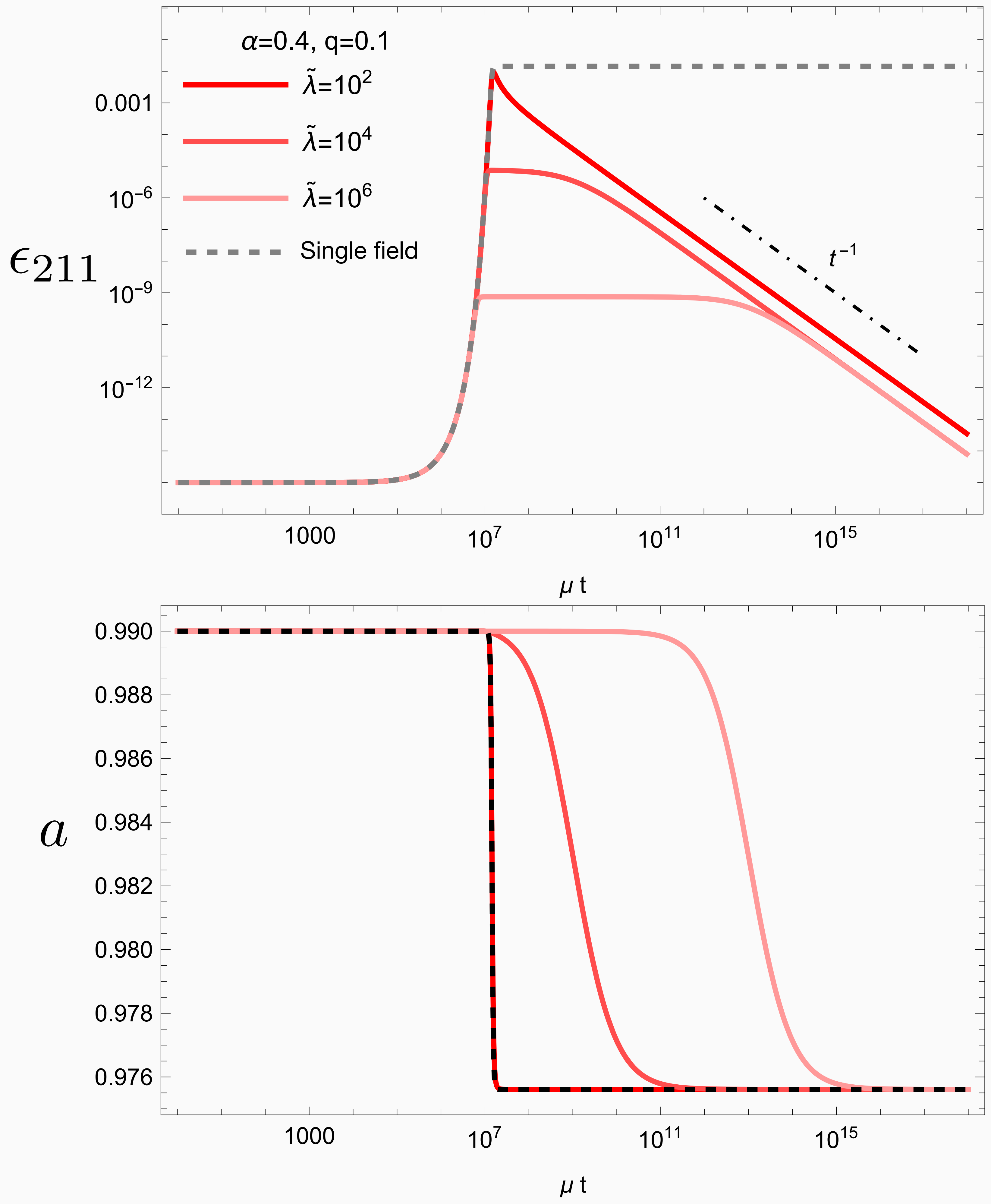
$$a' \simeq -\epsilon_{eq}\epsilon_{211}$$

Exponential growth $\quad \tau_{sr} = \mu\dfrac{\ln\epsilon_{eq} - \ln\epsilon_i}{\gamma_{211}}$

Quasi-equilibrium $\quad a' = -\epsilon_{eq}^2$

Power-law decay $\quad a - a_{crit} \simeq \dfrac{576\gamma_E^2}{\alpha^{16}}\left(\dfrac{4\alpha^2-1}{4\alpha^2+1}\right)^2\dfrac{1}{\mu t}$

$$\epsilon_{211} \simeq \frac{24\gamma_E}{\alpha^8}\frac{1-4\alpha^2}{1+4\alpha^2}\frac{1}{\mu t}$$



SR with Two Interacting Fields

Superradiance evolution

$$\dot{\epsilon}_{211} = \gamma_{211}\epsilon_{211} - (\boxed{\gamma_B} + \gamma_E)\,\epsilon_{211}^2 - \gamma_R\epsilon_{211}^3$$

$$\dot{a} = -\gamma_{211}\epsilon_{211} + \gamma_B\epsilon_{211}^2$$

- Interaction with bound states

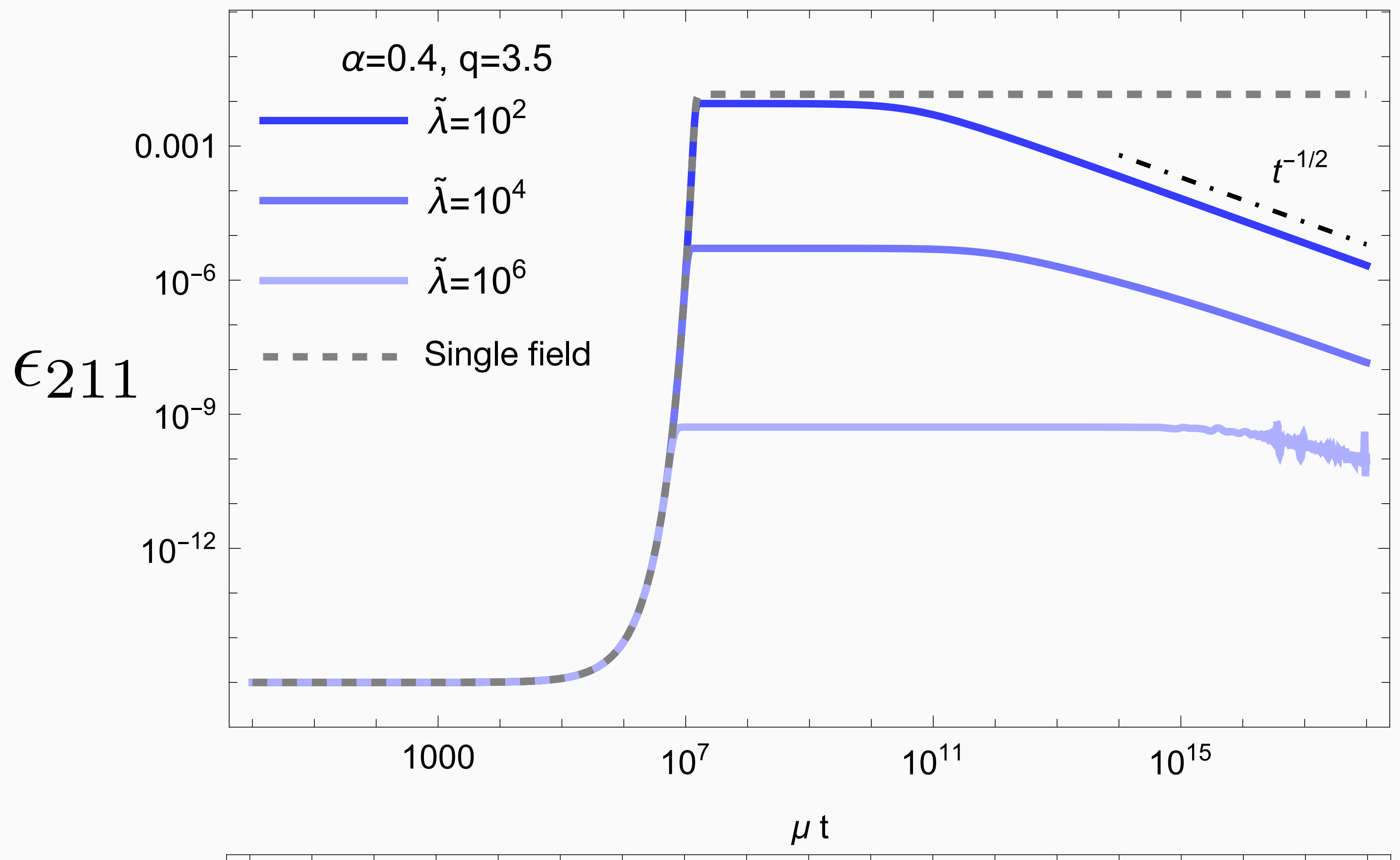
$$\epsilon'_{211} \simeq (\epsilon_{eq} - \epsilon_{211})\epsilon_{211} \qquad \epsilon_{eq} = \gamma_{211}/\gamma_B$$

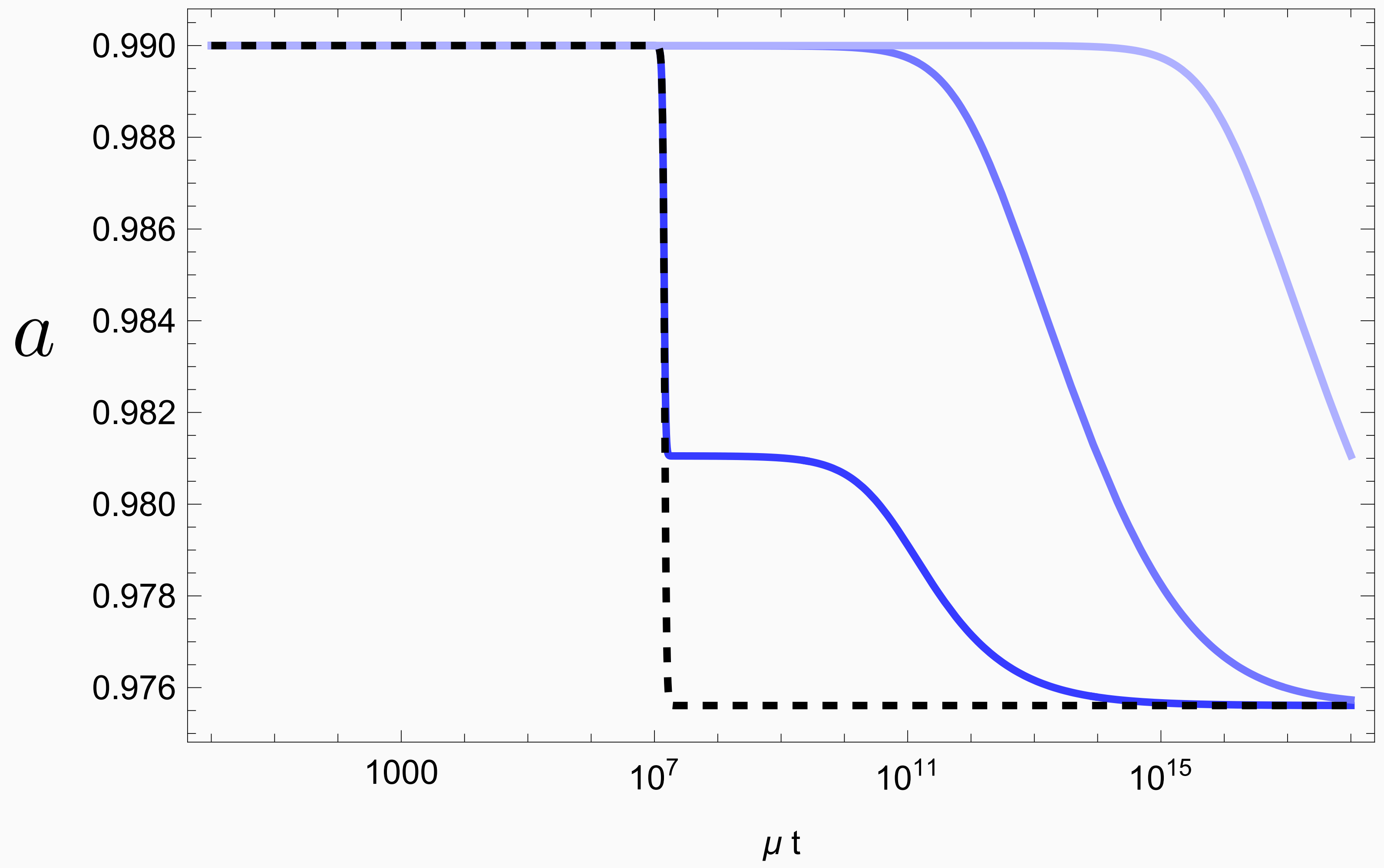
$$a' \simeq -(\epsilon_{eq} - \epsilon_{211})\epsilon_{211}$$

Exponential growth $\quad \tau_{sr} = \mu\dfrac{\ln\epsilon_{eq} - \ln\epsilon_i}{\gamma_{211}}$

Quasi-equilibrium $\quad a' \simeq 0$

Power-law decay $\quad \gamma_R$ dominates





SR with Two Interacting Fields

Superradiance evolution

$$\dot{\epsilon}_{211} = \gamma_{211}\epsilon_{211} - (\gamma_B + \gamma_E)\,\epsilon_{211}^2 - \boxed{\gamma_R}\epsilon_{211}^3$$

$$\dot{a} = -\gamma_{211}\epsilon_{211} + \gamma_B\epsilon_{211}^2$$

- 3 ψ radiation

$$\epsilon_{211}' \simeq (\epsilon_{eq} - \epsilon_{211})\epsilon_{211}^2 \qquad \epsilon_{eq} = \sqrt{\gamma_{211}/\gamma_R}$$

$$a' \simeq -\epsilon_{eq}\epsilon_{211}$$

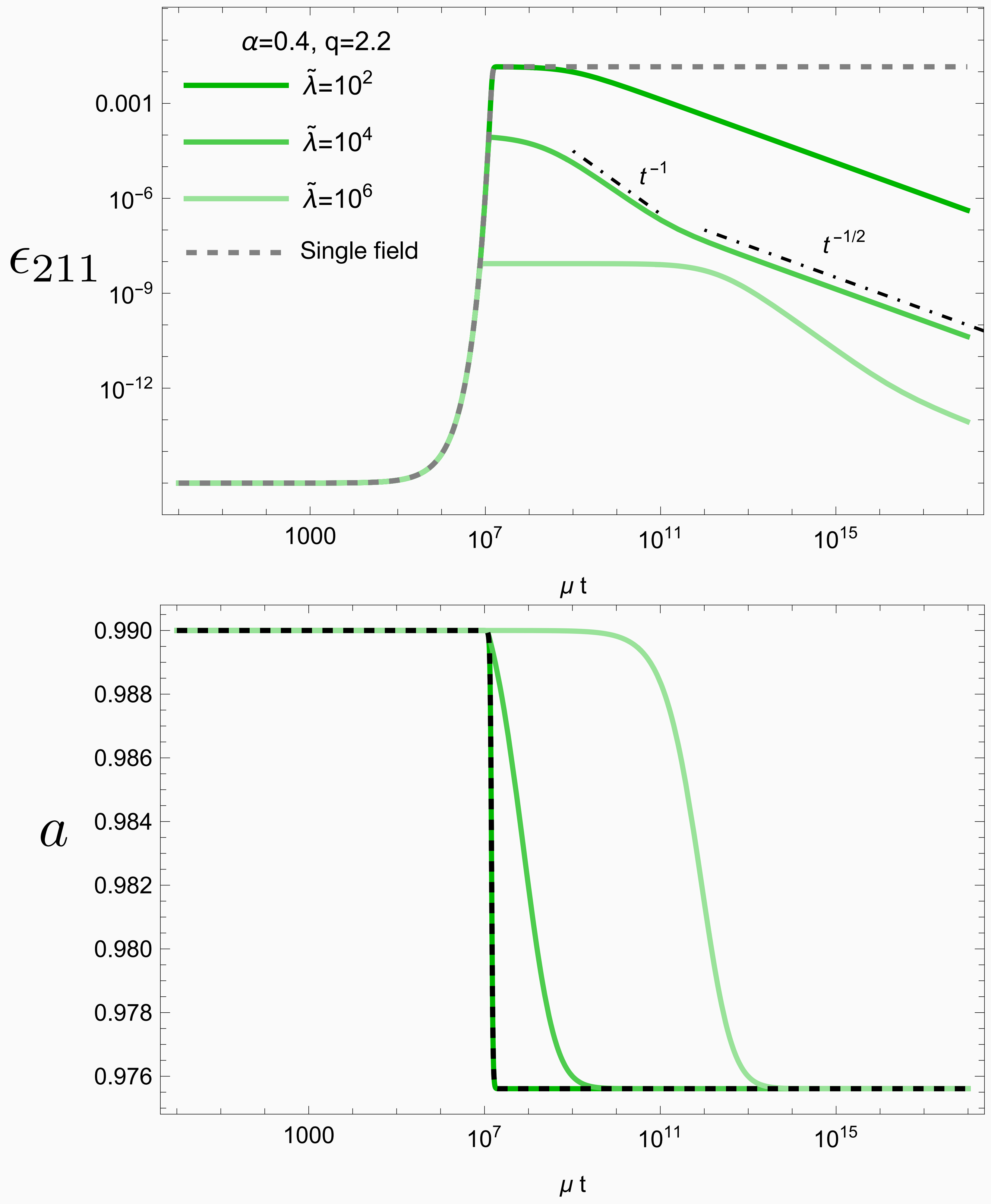
Exponential growth $\quad \tau_{sr} = \mu\dfrac{\ln\epsilon_{eq} - \ln\epsilon_i}{\gamma_{211}}$

Quasi-equilibrium $\quad a' \simeq -\epsilon_{eq}^2$

Power-law decay $\quad \epsilon_{211} \propto t^{-1}$

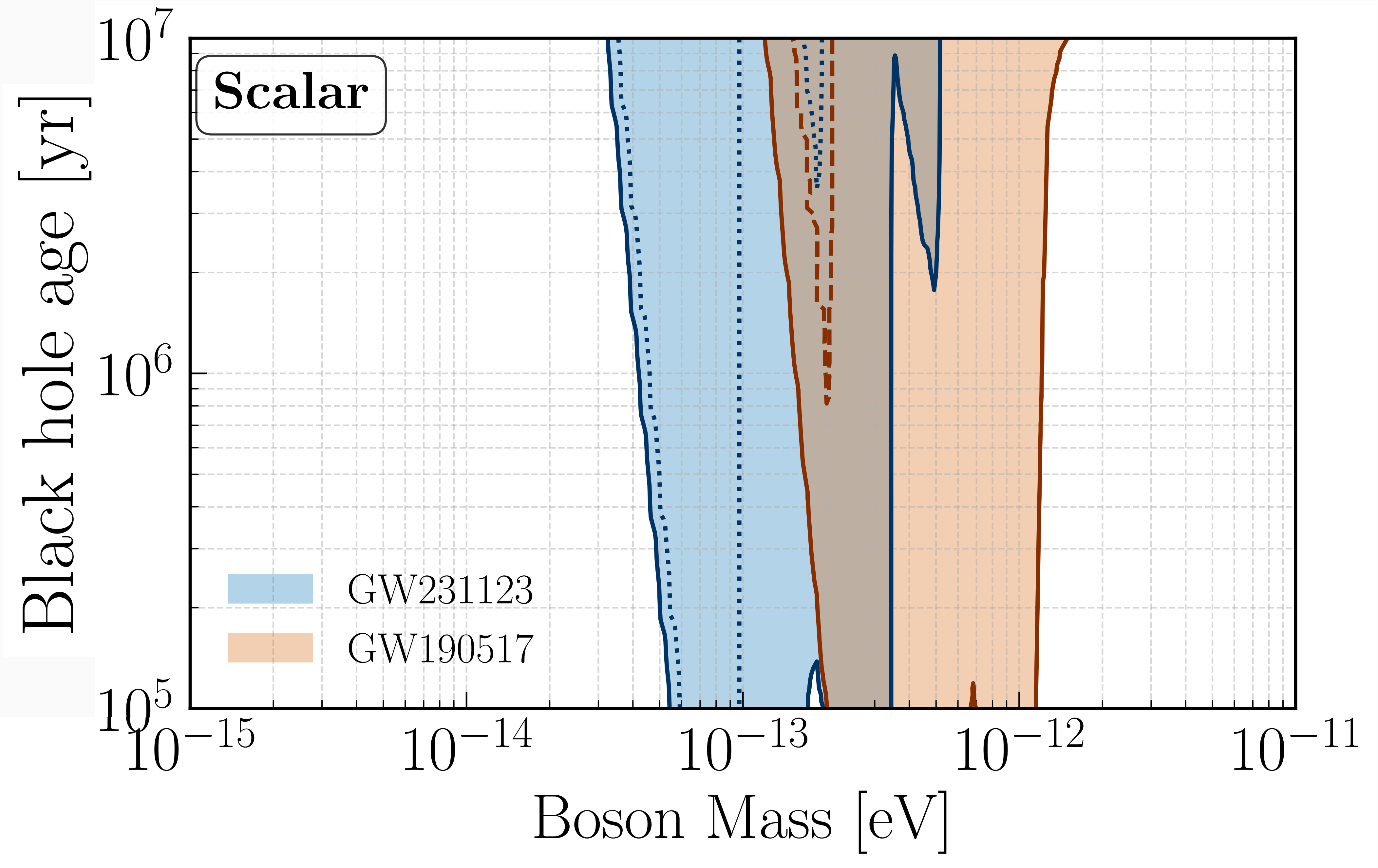
$$a_{th} = \frac{\alpha^8}{384\gamma_R}\frac{1+4\alpha^2}{1-4\alpha^2}$$

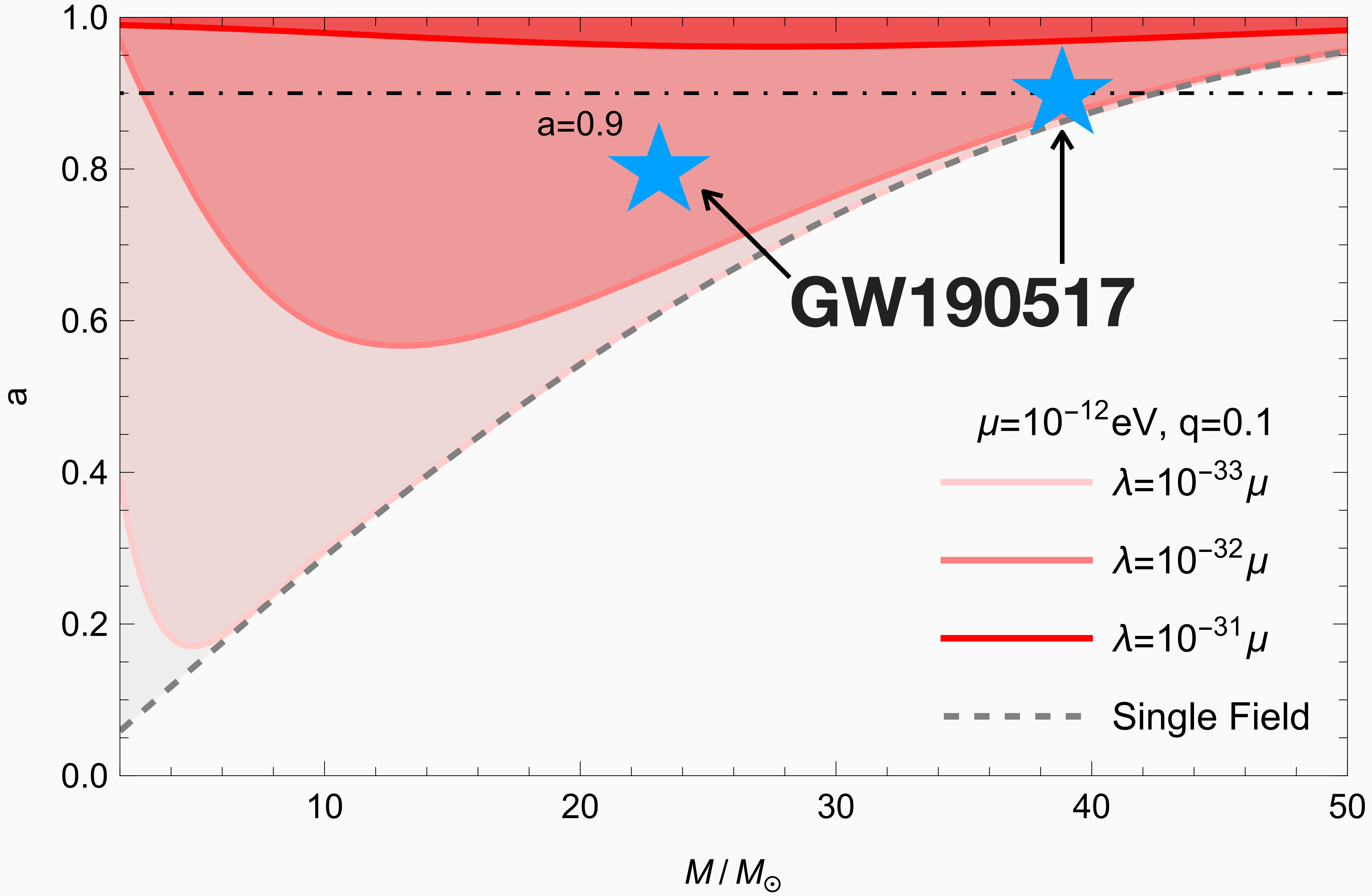
$$\epsilon_{211}' \simeq -\epsilon_{211}^3 \qquad \epsilon_{211} \propto t^{-1/2}$$



SR with Two Interacting Fields

- Implications on black hole spin





Summary

- Black hole superradiance provides a promising way of probing ultralight bosons.
- Black hole spin measurement, continuous gravitational wave searches, and gravitational waves from black hole binaries already imposed preliminary constraints on ultralight bosons.
- With a two-field toy model, we show that interactions generally suppress superradiant growth.
- Existing observational constraints should be revisited when ultralight bosons couple to other fields.

Summary

- Black hole superradiance provides a promising way of probing ultralight bosons.
- Black hole spin measurement, continuous gravitational wave searches, and gravitational waves from black hole binaries already imposed preliminary constraints on ultralight bosons.
- With a two-field toy model, we show that interactions generally suppress superradiant growth.
- Existing observational constraints should be revisited when ultralight bosons couple to other fields.

Thank you!